Atomic physics

Shaping atoms in optical lattices

Christopher Monroe

Imagine a bowl half full of water. Suddenly move the bowl slightly to the side, and a water wave rocks back and forth on the surface, largely retaining its shape. Suddenly squeeze the bowl down in size, and the surface wave 'breathes' in and out, approaching a sharp point when the wave reaches the centre. Quantum mechanics tells us that individual atoms are also waves, so it shouldn't be a surprise that atom wavepackets might be prepared and manipulated in a similar fashion — even though quantum atom wavepackets are not just ordinary waves; they describe in some sense the atom's existence.

It's a rare physical system that allows such control of individual atoms, but now both breathing and rocking motions have been produced, and observed, in optical lattices. By confining individual atoms in an

array of sites known as an optical lattice, researchers^{1–3} have observed the breathing motion of atomic wavepackets when the atoms were squeezed. The rocking motion of atoms in optical lattices was first observed⁴ in 1996. This shaping of atom wavepackets is of considerable interest to fundamental studies of quantum mechanics, and may also have future applications in nanometre-scale atomic lithography.

Optical lattices are formed by particular geometries of crossed laser beams, which interfere to produce alternating dark and bright spots of light about an optical wavelength apart. Under certain conditions, atoms are attracted to the bright spots due to electric dipole forces, resulting in a lattice of tiny atom traps — like a microscopic egg carton for atoms (Fig. 1). This remarkable form of matter resembles a solid-state crystal,

except that the periodic confining force is under precise external control, allowing some textbook solid-state phenomena to be cleanly observed⁵. In the above experiments, for instance, atoms were squeezed by suddenly increasing the power of the laser beams — thereby deepening the egg cartons. Because the atom wavepackets can't respond fast enough to the change, they pulsate in and out, intermittently occupying a much smaller region of space than they started out with.

Groups at the Max Planck Institute for Quantum Optics in Germany¹ and the US National Institute of Standards and Technology (NIST)² detected this breathing motion by observing the diffraction of a probe laser beam aimed at optical lattices of rubidium and caesium atoms, respectively. Even though the weak probe scatters very little from each individual atom, at certain angles the scattered light interferes constructively, owing to the periodic spatial order of the million or so atoms across the lattice (this effect is similar to diffraction from a grating).

If the atoms at each lattice site are then smeared out, the efficiency of the interfer-

Galactic structure

Bar serves cosmic scorpion

An ultraviolet image of the spiral galaxy, NGC4303 (below), has revealed a remarkable ribbon of star-formation activity that winds all the way into the central hub of the galaxy. But there is a twist to this observation in more ways than one, for it may yield clues to a suspected link between the structure of galaxies and the luminosity of their cores.

This striking image, obtained using the Hubble Space Telescope, was published last month (L. Colina *et al.* *Astrophys. J.* 484, L41–L45; 1997). Resembling a giant scorpion, with the galactic nucleus as its sting, the tapering

spiral structure consists of clumpy regions of bright emission — clear indicators of hot, newly formed stars.

NGC4303 is a barred spiral galaxy. The term derives from a linear grouping of stars, the 'bar', from which the curved arms are observed to emanate. Theoretical simulations suggest that the bars in spiral galaxies may serve a particular function, in gravitationally directing the flow of gas from the outer to the inner nuclear regions.

But the consequences of this gas flow can vary, depending on whether the galaxy's mass distribution gives rise to especially stable orbits, known as inner Lindblad resonances. For example, if such resonances exist, gas will accrue in their vicinity, resulting in the formation of a ring-shaped region of rapid star formation (or starburst) around the galactic centre. But in the absence of these resonant orbits, the bar of the galaxy can in principle direct the gas stream all the way into the nucleus.

No prizes, then, for guessing which of these cases fits NGC4303. Still more encouraging for this picture is the fact that a Hubble image of a second barred spiral galaxy, NGC3351 (above right), demonstrates the alternative ring-like morphology.

But what does this have to do with the brightness of different galactic nuclei?

Crucially, NGC4303 and NGC3351 are markedly different in their central regions.

NGC4303 has a luminous core, which is extremely compact by astronomical standards — at no more than about 25 light years across, its inner structural details remain invisible even to the Hubble Space Telescope. By contrast, there is no evidence for an active nucleus in NGC3351 at all.

So it seems likely that the spiral flow in NGC4303 is directly connected with the observed nuclear activity, either feeding a massive central black hole or fuelling an extremely bright cluster of massive young stars, similar to those seen throughout the spiral arm.

Karen Southwell

Figure 1 An optical lattice. Laser beams (red) intersect to form a standing-wave pattern of microscopic wells, which are about an optical wavelength apart and can hold individual atoms (left), and so manipulate them.

ence is degraded, reducing the intensity of the diffraction. The diffracted intensity is thus directly related to the atomic wavepacket width. Both groups observed that the intensity of the diffracted probe beam oscillated in time as the atom waves pulsed in the lattice.

A group at the University of Rochester in New York state³ observed similar oscillations in light scattered off sodium atoms, directly from the laser beams that make the optical lattice. When the atom wavepackets contract, they experience brighter regions of the lattice and so scatter more light; and vice versa. Common to all experiments, the scattered light undulations occurred at roughly twice the rate of rocking motion — which is the tell-tale sign of breathing motion.

In a bowl of water suddenly squeezed, the breathing motion is damped strongly by dissipation and dispersion of the waves. Similar effects wash out atom-wavepacket breathing in the optical lattices, limiting the number of observable oscillations to just a few. Although this decay does give valuable information about dissipative interactions between the atoms and the lattice, it can also mask interesting quantum effects of the motion which do not occur in water waves, such as quantum 'revivals' of the oscillation due to the anharmonic (non-parabolic) shape of the lattice wells. Nevertheless, the NIST group has very recently observed unambiguous quantum revivals in the rocking motion of the wavepackets⁶.

Optical lattices may someday find applications in lithography, where atoms could be released from the lattice sites and deposited onto a substrate to form useful miniature patterns. There remain many technical hurdles to cross before this is feasible, but because smaller is better in the lithography business, it is still worth investigating how small wavepackets can be shaped in an optical lattice. Heisenberg's uncertainty limit —

a trade-off between position and momentum uncertainty — places a natural quantum boundary on the size of a stationary atom wavepacket placed in the bottom of a well, a size that depends on the depth of the well. In typical optical lattices, this lower limit is around 10 to 100 nanometres.

But by shaping the atom wavepackets using the above techniques, the atoms can in principle be transiently squeezed down to much smaller sizes. Atoms in optical lattices

have not yet been squeezed below the quantum boundary, although related work in ion traps has allowed the squeezing of a single atom's wavepacket to about 1 nanometre — almost a factor of ten below the quantum boundary⁷.

Regardless of the prospects for atomic lithography, physicists are discovering many tools for harnessing atoms in this exotic form of matter. Several groups are now investigating optical lattices that are nearly free of dissipation and may more fully expose the quantum features of atomic motion, and allow squeezing well beyond the quantum boundary. As these recent atom-shaping experiments illustrate, optical lattices are becoming attractive playgrounds for quantum mechanics. □

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Protein folding

Folding with a two-stroke motor

George Lorimer

One of the hot problems in modern biology is how the molecular chaperone GroEL, along with its cohort GroES, facilitates the folding of other proteins. It is a wonderfully complex and highly dynamic process, the details of which are only beginning to emerge. Two papers by Xu *et al.*¹ and Rye *et al.*² from Yale University (pages 741 and 792 of this issue) mark considerable progress in our understanding, and again demonstrate the power of crystallography¹ coupled to clever mutagenesis². They also remind us that we still have lots to do before the mechanism of this remarkable two-stroke folding machine can be considered to be 'defined'.

The interaction between GroEL and GroES is necessary for certain proteins to fold under otherwise non-permissive conditions³. The subunits of both proteins are heterologously assembled into heptameric rings^{4,5}. In the case of GroEL, two rings stack back-to-back (isologously) to form the native 14-mer, enclosing two large, non-contiguous central cavities. Each monomer unit consists of three domains. The larger 'equatorial' and 'apical' domains are linked

through a smaller 'intermediate' domain.

GroES resembles an upturned saucer⁵, with seven unstructured and mobile loops⁶ extending from the rim. In the presence of nucleotide⁷, GroEL and GroES interact through the mobile loops to form both an asymmetrical GroES₇–GroEL₁₄ complex⁸, the structure of which is now reported by Xu *et al.*, and a symmetrical GroES₇–GroEL₁₄–GroES₇ complex^{9,10}.

Three-dimensional reconstructions of electron-microscopic images at 30 Å revealed that, accompanying the binding of ATP and GroES, there is a massive upward movement of the GroEL apical domains¹¹. Xu *et al.* now show that this is due to a twisting, en-bloc movement of the apical domains around a 'hinge' at the junction of the intermediate and apical domains. This movement creates an enlarged cavity — known as Anfinsen's cage (Fig. 1) — in which the unfolded substrate protein, at least transiently, resides^{12–14}. But the system is dynamic, and when the GroES cap¹⁴ dissociates from the proximal *cis* GroEL ring with each cycle (as occurs when ATP binds to the distal *trans* GroEL ring²), the substrate pro-