Toward Atom Chips

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The spectacular success of microelectronics has demonstrated the enormous potential of miniaturization for turning basic physics into applications. Today, researchers are exploring further miniaturization to nanometer and even atomic scales. A new field of research explores the behavior of clouds of ultracold atoms (which behave as matter waves) above the surface of a microchip. The chip generates a magnetic and electrostatic field that can be used to guide and manipulate the matter wave. This setup may allow the construction of matter wave interferometers on microchips; such “atom chips” may serve as sensitive probes for gravity, acceleration, rotation, and tiny magnetic forces.

In 1995, Weinstein and Libbrecht published a simple and striking idea (1) for the storage, guidance, and manipulation of ultracold atoms near the surface of a chip containing microfabricated conductors. At the time, thermal clouds of ultracold atoms with temperatures below 0.001 K were routinely stored in magnetic traps. It was conceivable that the required magnetic storage fields could also be generated with microfabricated wires. But the real thrill was the vision of a new kind of chip based on atoms that behave like quantum mechanical matter waves rather than classical particles. However, atomic clouds could not yet be prepared at the very low temperatures required for quantized motion.

The discovery of Bose-Einstein condensation provided a possible solution. In such a condensate, the matter waves of the atoms overlap and all the atoms are indistinguishable, forming a macroscopic matter wave. A microtrap would be able to carry a condensate of several tens of thousands of atoms. In 2001, two groups succeeded independently in loading Bose-Einstein condensates into a microtrap (2, 3). The door was opened for the field of integrated atom optics (4–6).

Magnetic trapping requires the magnetic moment of the atoms to be antiparallel to the local magnetic field. The atoms then become trapped at the local minimum of the absolute value of the field. Different microtraps can be constructed. In the simplest microtrap, the circular magnetic field of a straight conductor is added to a homogeneous bias field oriented perpendicular to the conductor (see the first figure). The two fields compensate each other along a line that runs parallel to the conductor and defines a “waveguide potential.” The atoms are trapped along this line.

In typical microtrap experiments, the conductor is driven with a few tens of milliamps, and the bias field is a few gauss. Under these conditions, the waveguide potential is separated from the conductor surface by several micrometers. The atom cloud thus floats above the chip and is thermally isolated from it, because the experiments are performed in a vacuum.

The miniaturization of the traps results in extremely strong magnetic field gradients and steep potentials. When a magnetic offset field is added parallel to the waveguide, the radial confinement becomes parabolic, giving rise to harmonic oscillations (see the first figure). For rubidium, the most commonly used element on atom chips, oscillation frequencies of 1000 Hz to tens of thousands of Hz are accessible. The potential structure along the axis of the waveguide can be manipulated by adding further conductors perpendicular to the waveguide axis. For example, a pair of additional conductors would close the waveguide at each end, resulting in three-dimensional confinement on a chip. More complex structures can be used to control the momentum and shape of the atomic matter waves (see the second figure) (7).

The steepness of the magnetic trapping potential determines the separation of the energy levels in the trap and sets the time scale for the atomic dynamics. Fast “circuits” require tiny traps, and tightly confining traps made of very thin conductors are thus desirable.

But how small can the traps be made? The fabrication of conductors down to the micrometer scale causes no particular difficulty. However, interactions of the conductors and the substrate surface (which are at room temperature) with the ultracold atoms must be considered. Theoretical considerations suggest that when the distance between the chip and the atom cloud is less than 1 µm, the lifetime of the trap should be reduced substantially by magnetic field fluctuations (8). Surprisingly, pronounced surface effects already occur at much larger distances of 100 µm and more. If a condensate is released into a waveguide potential, it does not form a smoothly expanding atomic cloud but fragments into little localized blobs. This effect (9) is probably caused by geometric imperfections and inhomogeneities in the conductor that force the current to deviate from a straight line. As a result, the waveguide becomes rough and bumpy. Condensates may thus serve as very sensitive probes for

**Bose-Einstein condensate on a microchip.** (Top) The wider conductors (dark blue) generate a waveguide for the atomic cloud (a Bose-Einstein condensate, shown enlarged by 10 times). The finer conductors (bright blue) generate micropotentials such as beam splitters, double-well potentials, and lattices. They can be loaded by adjusting the current in the outer conductors (7). (Bottom) Photograph of the complete atom chip (7), a section of which is shown schematically in the top panel.

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sensing the path of a current in a conductor or in microfabricated heterostructures.

Another limit to miniaturization is set by the electrostatic attraction between atoms that are adsorbed and polarized at the chip surface. These forces become effective at micrometer-scale distances. A final limit is set by weak, attractive dispersion forces between the chip surface and the atom cloud. They rapidly set in at distances of several hundred nanometers and are difficult to compensate because of their strong spatial dependence.

Given these limits, there are several directions for future developments. Microfabrication can be improved to reduce imperfections and obtain more homogeneous current conductors—for example, by switching from electroplating to direct vapor deposition. However, basic atom chips can already be created with existing technology. Spatial fluctuations of the magnetic field due to imperfections of the conductors average out over distances that are large relative to the size of the imperfections. A waveguide far from the chip surface exhibits a smooth potential. This smooth waveguide can be combined with steep and thin potential barriers, generated on an extra chip next to the atomic cloud. Such a geometry, in which waveguide and potential barriers are generated by separate chips, is far less sensitive to wire imperfections than a single-layer chip. Matter-wave interferences have recently been observed with such a setup (10).

Atomic matter waves on chips can also be manipulated with electric fields (11) or even laser beams (12). Both induce an electric dipole moment through which the interaction with atoms is achieved. Combinations of magnetic, electrostatic, and optical potentials on atom chips remain to be explored. For example, temporally controlled lasers can be used to produce potential barriers in magnetic waveguides.

Instead of manipulating a condensate as a whole, it can also be used as a zero-temperature reservoir for single atoms. Such an atom laser could provide a coherent source for performing optics with single atoms. To measure and detect single atoms after they have been manipulated, a detector with single-atom sensitivity would be desirable. Possible approaches include optical ionization with light from the tip of an optical fiber followed by ion detection, and detection of single atoms in miniaturized optical resonators. According to theoretical studies, present-day technology should permit the construction of microcavities that can detect a single atom in the trap (13).

Which of the various ideas will prove most successful remains to be shown. As in every young field of research, atom chips will be good for future surprises.

References

Paleontology

Homoplasy in the Mammalian Ear

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The similarity among structures that arose through independent evolution instead of descent from a common ancestor is termed homoplasy and is a major feature of evolutionary morphology. A fascinating but very difficult question facing evolutionary biologists is whether a complex structure would be less likely than a simple structure to undergo independent homoplastic evolution (1). On page 910 of this issue, Rich et al. (2) partially answer this question with their analysis of the dentary bone from the lower jaw of an Early Cretaceous fossil monotreme called Teinolophos, an extinct relative of Australia’s modern platypus and echidna. The new fossil find offers fresh anatomical evidence to support the hypothesis that a key evolutionary innovation among modern mammals—the separation of the middle ear bones from the mandible—must have evolved independently among the monotreme mammals and the therians (marsupials and placentals).

The tiny bones of the middle ear that are used for hearing render modern mammals—including placental, pouched marsupials, and egg-laying monotremes—unique among vertebrates (2). The middle ear bones are the malleus, incus, and stapes, and in addition there is the tympanic bone, which supports the tympanic membrane, enabling it to receive sound. The tympanic, malleus, and incus are homologous to bones in the mandible and jaw hinge (the angular, articular, and quadrate, respectively), which are required for feeding in nonmammalian vertebrates (3–5). There is also extensive evidence from fossils of extinct cynodont and mammaliform relatives of modern mammals suggesting that the angular, articular, and quadrate bones in these creatures were used for hearing while still attached to the mandible and jaw hinge (6, 7). Evolution of the mammalian jaw joint and middle ear represents a classic example of the phylogenetic transformation of a complex functional structure that can be read directly from fossil evidence.

However, alternative interpretations have waxed and waned about how these middle ear bones got separated from the mandible during early mammalian evolution. The structure of the middle ear is so complex and unique that some researchers consider the separation of the middle ear bones from the mandible to be the strongest synapomorphic (shared derived) characteristic of living mammals (7, 8). They also propose that the monotreme, marsupial, and placental lineages split after their common ancestor had acquired this key feature. This view has been contested by others who favor multiple and independent acquisitions of the mammalian middle ear bones after the divergence of monotremes, marsupials, and placentals (6, 9).

In premammalian cynodonts and such primitive mammaliforms as Morganucodon (see the figure), the middle ear bones were accommodated within an internal trough in the mandible [see (2)]. From dental evidence, Teinolophos is unequivocally placed in the monotreme lineage (2, 10). But like Morganucodon and very much unlike living monotremes, Teinolophos exhibits a well-developed internal mandibular trough, suggesting that the angular (tympanic), the articular (malleus), and other “reptilian” jaw bones remained attached to the mandible through ligaments long after Teinolophos and living monotremes split from the common ancestor of marsupials and placentals. Another recent study shows that the middle ear bones were no longer accommodated by the internal mandibular trough but were still linked via the ossified Meckel’s cartilage to the mandible in some triconodont mammals. These mammals evolved after the divergence of the monotreme and therian (marsupial and