The second avenue is phylogenetic. The evolutionary scheme we have outlined implies that the transition from great appendage to labrum happened once in the common ancestor of all living arthropods apart from the pycnogonids, which must therefore be very basal in evolutionary terms. But if the pycnogonids truly are the sister group of the spiders and scorpions (which some molecular data suggest[9]), then the results of Maxmen *et al.* will be hard to square (Fig. 2). Testing the phylogenetic position of pycnogonids is therefore crucial.

The conclusions of Maxmen *et al.* overturn entrenched ideas about the body plan of the sea spiders and, furthermore, lend support to some controversial theories of arthropod evolution. Unlike their terrestrial analogues, sea spiders lack a poisonous bite, but this paper is bound to inject venom into what is already one of the most controversial of all zoological topics. ■

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QUANTUM PHYSICS

Atom waves in passing

Maarten DeKieviet and Joerg Schmiedmayer

Matter-wave interferometers are unique tools for exposing particles acting like waves — one of the stranger facets of quantum theory. They can even measure the quickening of an atom's 'pulse' as it flies past a surface.

Particles sometimes act like waves, and waves sometimes act like particles. This phenomenon, known as wave–particle duality, may seem to confuse what are (to everyday experience at least) two separate and unambiguous concepts. But 100 years after Albert Einstein first introduced the idea of waves behaving like particles to explain the photoelectric effect, and more than 80 years after the French physicist Louis de Broglie proposed the converse behaviour, wave–particle duality has become a staple food of the quantum diet. Writing in *Physical Review Letters*[1], John Perreault and Alexander Cronin expose a further experimental ramification of the effect, by measuring the shift in phase — a wave property — of an atom as it flies past, and interacts with, a surface.

In doing so, they take advantage of matter-wave interferometry, a technique that has in recent decades given fresh impetus to studies of the wave-like nature of particles. Pioneered for simple particles such as electrons[2] and neutrons (ref. 3 and references therein), the technique has since been extended to larger particles such as atoms and molecules (ref. 4 and references therein).

Interferometry as a generalized technique involves the superposition of two waves to gain information about their relative phase — where in their cycle they are in relation to each other. A simple analogy is a zip-fastener: for proper zipping, the teeth of one strand must fit perfectly with those of the other. If, however, they are shifted such that the teeth oppose each other, the zipper won't close. Analogously, if the peaks of one wave are next to the troughs of the other, the waves are perfectly out of phase, and their amplitudes cancel out — they interfere 'destructively'. Conversely, if the two waves are perfectly in phase, with the peaks and troughs matching, they interfere constructively to produce a net amplitude that is the sum of the two individual amplitudes.

In an interferometer, an incoming wave is split into two branches. One of these branches is subjected to an outside influence that slows down or speeds up the atom-wave's cycle, or pulse, thus shifting its phase relative to that of the other branch. These two branches are then brought back together and interfere, the amplitude of the resulting wave being proportional to the degree to which the two waves are in phase. Generally in wave mechanics only intensities — the squares of the amplitudes — can be measured, so phase information is lost. The power of interferometry is that it transforms a shift in phase to a change in amplitude, which can be measured as change in intensity.

And so it is in Perreault and Cronin's experiment[1]. They make use of a Mach–Zehnder interferometer, in which a nanoscale grating is used to diffract atomic waves, thus acting as a matter-beam splitter[5]. The authors inserted a further 250-nm-thick membrane with thousands of 50-nm-wide slits into one branch of this interferometer. As they pass through this additional membrane, the atoms experience a weak, attractive van der Waals force through electronic coupling with the membrane's walls. This interaction speeds up the atoms' pulse — the phase of the atom-wave becomes shifted with respect to the free-atom wave in the interferometer's other branch. From the measured interference, the phase shift caused by the atom–surface interaction can be exactly quantified.

This measurable change in the interference pattern arises from an atomic interaction that occurs over a distance up to 1,000 times that of an atomic diameter. Perreault and Cronin are, to their knowledge, the first to determine directly the phase shift caused by the van der Waals interaction between an atom and a surface. The acceleration towards the surface of the channels experienced by the sodium atom-waves is more than a million times that caused by Earth's gravitational field. The channels are, however, very short, so the actual time difference measured by the interferometer is only about 100 attoseconds (10^{-16} seconds). Contrasting this with the overall flight time through the device of around one millisecond gives an idea of the exquisite sensitivity possible with interference experiments. This experiment is a beautiful example of the many tools that are being developed in a true renaissance in the study of atom–surface interactions[6].

The potential impact of such work stems from its connection to the fields of nanotechnology and atom optics. Nanometre-scale structures could lead to smaller transistors and motors, or the ability to assemble molecules atom by atom. Exploiting the wave behaviour of atoms could lead the way to more precise gyroscopes for navigation, gravity gradiometers for subterranean mapping and other field sensors. The work of Perreault and Cronin[1] lies at the intersection of these two fields, putting a limit on how small nanotechnological and atom-optical devices can be made before the van der Waals interaction disrupts their operation. ■

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