

females spend a lot of time — tend to overlap with shipping lanes, and because the energy demands of motherhood exacerbate the ill-effects of any serious injury.

Because there are so few right whales left in the North Atlantic, the US National Marine Fisheries Service (NMFS) has already adopted a policy that emphasizes the value of each whale<sup>3</sup>. Consequently, although the NMFS has not attributed any special significance to mature females, they have interpreted the US Endangered Species Act of 1973 to mean that efforts must be taken to prevent any human-related whale deaths. Indeed, the NMFS initiated an extensive whale-tracking programme in 1996 to minimize such deaths by keeping ships away from sites of whale sightings<sup>4</sup>. But because more than 60% of North Atlantic right whales have scars from entanglement in fishing gear, such as lobster pots and sink gillnets (Fig. 2), environmental groups such as the Sierra Club in Massachusetts argue that simply alerting ships to the presence of whales does not provide adequate protection<sup>5</sup>. Moreover, the US Humane Society is currently suing the NMFS over its failure to address entanglement-related deaths, and has won an initial favourable ruling because the NMFS's current plan to minimize whale deaths is inadequately specified.

In short, Fujiwara and Caswell's study<sup>1</sup> provides both hope and despair. A population that was thought by many to be doomed because of terribly low numbers can probably be saved. But the fact that just a few human-induced deaths could tip the balance towards the population's demise exposes a familiar story: a government agency is charged with capitulating to a powerful industry, but claims to be doing all it can. Throughout the world, harvest of endangered species, whether accidental or deliberate, is permitted because the measures needed to prevent such deaths — such as closing down lobster fisheries — are seen as too draconian<sup>6</sup>. But according to environmental groups such as the Sierra Club, these extreme measures are not necessary<sup>5</sup>. They suggest instead that technical improvements in fishery operations may be sufficient, for example using lighter lines that break more easily when whales become entangled.

Population biology and demographic studies can predict how much better a population would fare if certain numbers of individuals were spared. Unfortunately, it is uncommon in conservation biology<sup>6</sup> to get the kind of clarity provided by Fujiwara and Caswell's analysis. Conservation often means protecting individual animals from death caused by human activities. Fujiwara and Caswell have shown us the importance of highlighting what might at first glance seem like insignificant numbers of deaths. Their approach promises to be useful for everything from grizzly bears to spotted

owls to sockeye salmon — species for which similar mark-recapture data are available and which have in some places dwindled to such low numbers that saving individual lives could matter. ■

Peter Kareiva is at The Nature Conservancy, 217 Pine Street, Seattle, Washington 98101, USA.

e-mail: pkareiva@tnc.org

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## Laser science

# Physics at the attosecond frontier

Yaron Silberberg

Ultrashort laser pulses allow physicists and chemists to watch fast molecular motion as it happens. But many fundamental atomic processes are even faster and require the shortest pulses ever created.

As every photographer knows, a flash of light can stop the action. Just as a fast flash lamp can freeze the image of a bullet in mid-flight, so short laser pulses can be used to probe fast molecular motion. It is no surprise, then, that laser scientists have been pushing for ever-shorter pulses of light in order to follow ever-more rapid processes. The quest has taken us from the first sub-picosecond (1 picosecond is  $10^{-12}$  s) pulses, more than a generation ago, to the development of femtosecond optics (1 femtosecond is  $10^{-15}$  s). These time periods are hard to imagine, but a femtosecond is to a minute what a minute is to the age of the Universe.

Femtosecond pulses led to femtochemistry, the experimental study of fast chemical reactions and molecular dynamics. Even the fastest molecular vibrations appear com-

pletely still when probed with a pulse lasting a few femtoseconds. Now, we are entering the era of attosecond pulses (1 attosecond is  $10^{-18}$  s). On page 509 of this issue Hentschel *et al.* describe<sup>1</sup> the generation and use of pulses lasting 650 attoseconds, in what might be the dawn of attophysics — the study of dynamics on timescales fast enough to follow electronic motion within atoms.

The road from picosecond to femtosecond light pulses has seen laser technology evolve towards lasers that emit light with greater 'spectral' width — that is, covering a wider range of wavelengths. A short pulse results when all the spectral components in the light beam interfere in a way that adds up to a single burst of light. The duration of this pulse is inversely proportional to the spectral width — so a wider spectral

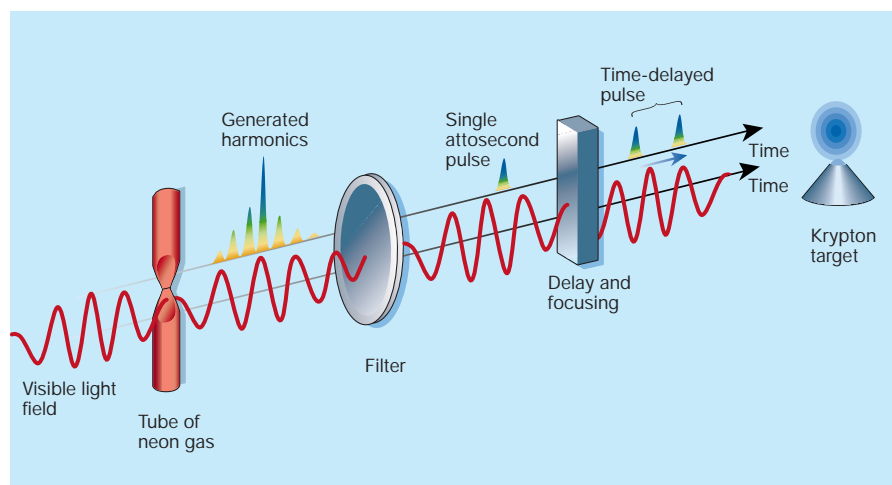


Figure 1 Generating and using attosecond laser pulses. In their experiment, Hentschel *et al.*<sup>1</sup> shine an ultrashort visible light pulse on a gas of neon atoms to produce higher frequency 'harmonic' radiation (rainbow-coloured pulses) at ultraviolet and X-ray wavelengths. The visible and harmonic pulses pass together through a zirconium filter, which reduces the train of harmonic pulses to a single attosecond pulse (1 attosecond is  $10^{-18}$  s). Both the attosecond pulse and the optical beam are focused onto the krypton target where they accomplish the very first attosecond measurement. The authors monitor the attosecond dynamics of photoelectrons emitted by the krypton gas by varying the delay between the attosecond and visible pulses.

span means a shorter pulse. This approach reached its natural limit when the spectral span of the laser became a significant portion of the visible spectrum. This is because the pulse cannot be shorter than the period of the optical wave, which is a few femtoseconds in the visible range. So it was obvious that a different approach would be needed to break into the attosecond range.

The latest advances are based on research into 'high-order harmonics' of femtosecond laser pulses. Nearly a decade ago<sup>2,3</sup> physicists used intense femtosecond pulses to ionize a rare gas (such as neon) and found that new electromagnetic waves were generated at much higher frequencies (and shorter wavelengths) alongside the original optical pulse (at visible and short infrared wavelengths). It is fairly straightforward to produce these high-order harmonics, whose wavelengths extend well into the ultraviolet and X-ray range, but measuring and controlling them to produce ultrashort pulses is much harder.

Precise analysis of the way the gas atoms interact with the laser field requires careful application of quantum mechanics, but a simple model developed in 1993 by Paul Corkum<sup>4</sup> (one of the authors of the Hentschel *et al.* paper) provides some insight. In this model, the original laser pulse tears an electron away from an atom, and the freed electron moves in response to the laser field, being accelerated and decelerated as the electromagnetic wave oscillates. The new harmonics are generated when the electron collides with the ion it left behind. This radiation is termed harmonic because its frequencies are multiples of the original laser frequency.

Corkum argued that electrons that are ejected precisely at the peaks or the crests of the optical pulse are much more likely to radiate. So the radiation is produced in very short bursts, which occupy just a fraction of the optical cycle. These short bursts explain the much wider spectral span of the high-order harmonics. The bursts are estimated to last some 100 attoseconds, and are expected to appear twice in each optical cycle of the original pulse. Last year, two experiments confirmed that the duration of these pulses is in the attosecond range<sup>5,6</sup>.

Attosecond pulses produced in this way appear as a train of pulses separated from each other by half an optical wavelength. However, most experiments require isolated pulses. The key to isolating a single attosecond pulse is to start with a very short pulse of just a few optical periods. Such a pulse produces only a few attosecond bursts, and it is possible to select just one by appropriate filtering (Fig. 1). So Hentschel *et al.*<sup>1</sup> start with a 7-femtosecond optical pulse and estimate that, after filtering, more than 90% of the energy of the new radiation they produce is contained in a single 650-attosecond pulse.

But that's not all. After generating an

isolated attosecond pulse, Hentschel *et al.* shine it, together with the optical pulse that generated it, onto krypton gas, to perform the first attosecond measurements of an electronic process. While varying the delay between the two pulses with attosecond accuracy they monitor the energy spectrum of any photo-electrons ejected from the gas. (Changing the difference between the paths taken by the two pulses by 0.3 micrometres changes the delay between the two pulses by 1 femtosecond, so it is easy to control the pulse timing in this way.) With this measurement Hentschel *et al.* achieve three important things: they characterize the attosecond pulse; they measure the detailed structure of the optical field; and they perform the first sub-femtosecond measurement of electron dynamics associated with photo-ionization.

What sort of experiments are possible with attosecond pulses? Should we expect an explosion of new results? At these timescales, chemistry is essentially frozen in time, so the only dynamics to be studied are those of electrons, as they are much lighter and faster than nuclei. Most femtochemistry measurements are based on the pump-probe method: one pulse sets the system into motion, and a second one probes it after a controlled delay. But this approach is not possible with attosecond pulses: they are just too weak. Moreover, manipulating

such pump and probe pulses is harder to do because their wavelength is in the X-ray range, for which traditional optical tools (such as lenses and beamsplitters) do not exist.

The work of Hentschel *et al.* hints at the likely direction that attophysics will take in the near future. They achieve attosecond measurements by carefully timing the delay between an attosecond pulse and an optical pulse. Yet the experiment also demonstrates the difficulties associated with this approach, because the information in the attosecond pulse, the optical field and the physics of the interaction are all interwoven. The interpretation of such experiments will necessarily be complex, and any physical information will have to be derived indirectly. We have now entered the attosecond world, but we will need a better guidebook to help us find our way around it. ■

Yaron Silberberg is in the Department of Physics of Complex Systems, Weizmann Institute of Science, 76100 Rehovot, Israel.

e-mail: yaron.silberberg@weizmann.ac.il

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## Oceanography

# Sea snow microcosms

Farooq Azam and Richard A. Long

Marine bacteria can respond to organic particles in sea water, creating hotspots of bacterial growth and carbon cycling. This microscale behaviour should be included in models of the oceanic carbon cycle.

Oceanographers exploring the ocean's carbon cycle, and its role in climate change, do so at a grand scale. Satellite measurements of ocean colour are used to infer carbon dioxide (CO<sub>2</sub>) assimilation into organic matter by photosynthetic organisms — a process known as carbon fixation. Instruments on ships and buoys assess how fast carbon is being fixed, what fraction is respired back by marine organisms to CO<sub>2</sub>, and what fraction of organic matter sinks into the deep ocean, isolating its carbon from air-sea exchange for millennia. These studies paint a broad-brush picture of carbon cycling in the oceans, but they cannot predict future changes — in response to increases in atmospheric CO<sub>2</sub>, for example.

Without looking at the ocean at the finer scale we cannot hope to understand or predict these changes<sup>1,2</sup>. It has long been recognized that bacteria are responsible for consuming much of the organic matter in marine systems. But the current climate-

change models ignore how bacteria in the ocean respond to the patchy distribution of organic matter. This may well be a serious omission. A simulation, reported in *Limnology and Oceanography* by Kiørboe and Jackson<sup>3</sup>, greatly reinforces our understanding of how marine bacteria interact with the patchy distribution of organic matter in the ocean. The results indicate that the response of bacteria to sinking organic particles has a big influence on the oceanic carbon cycle.

Kiørboe and Jackson<sup>3</sup> model the interactions of bacteria with marine snow (Fig. 1, overleaf). A cubic metre of sea water contains thousands of these rapidly sinking flakes<sup>4</sup>. They are the main vehicle for transporting organic matter, and its associated carbon, from the upper ocean<sup>4</sup> (where it readily exchanges with the atmosphere) to the ocean floor (where it eventually settles in sediments). The fate of marine snow, and the depth at which its carbon is converted back to CO<sub>2</sub> by bacteria, is critical for under-