neutral, the gluons themselves carry colour charges (Fig.1).

The soul of QED is the electromagnetic field. When Faraday and Maxwell proposed this field, their contemporaries found it very abstract and mysterious. But as antennas were devised that danced to its tune, the electromagnetic field came to seem undeniably real and almost tangible.

Can one devise antennas for the colour fields of the strong interaction? It is not possible to do this directly, because the wavelengths involved are ridiculously small — 10^{-14} cm and below, much smaller than X-rays or even ordinary gamma-rays. Fortunately, colour coherence provides an indirect path to the goal.

What follows is an example of colour coherence which makes an especially vivid impression, owing to its use of photons and gluons in contrast.

Usually, when a high-energy electron and its antiparticle, a positron, annihilate, two narrow sprays of particles (jets) emerge, produced by a short-lived quark–antiquark pair. Some slow-moving particles are also left behind. The number of particles produced at a given time and place measures the strength of the colour field there, much as an antenna's response measures the strength of electromagnetic fields. This multiplicity is roughly proportional to the intensity, or energy, of the field, which grows as the square of its magnitude. So, in effect, the slow-moving particles provide a peculiar form of antenna — one that is fairly crude, but unique in its sensitivity to exceedingly short-wavelength colour fields, ready-made and very cheap.

This antenna has been used to distinguish between coherent and incoherent fields, which are produced in two slightly rarer cases of electron–positron collision. In about ten per cent of the events, there is a third jet containing several strongly interacting particles. This third jet signals the radiation of a colour gluon. Still more rarely, in fewer than one per cent of the events, an energetic photon accompanies the quark and antiquark (Fig. 1). Fortunately, as millions of electron–positron annihilation events have been studied, there are many examples of both rare types available for analysis.

Colour charge, like electric charge, is conserved. Because the original electron and positron had zero colour charge, the colour charges of the annihilation products must add up to zero. When the quark and antiquark are accompanied by a photon, their colour charges must be equal and opposite, as the photon is colour neutral. The positive charge (red, say) creates a red colour field that points away from it, whereas the field of the negative red charge points towards it. In the region between, these two contributions reinforce each other — the fields are coherent. But when the quark and antiquark are accompanied by a gluon, their colour charges are generally of completely different types, not equal and opposite, and the fields between them do not reinforce each other.

QCD predicts, therefore, that more particles will be produced between the quark and antiquark jets when they are accompanied by a photon, as compared to when they are accompanied by a gluon jet. Just such an effect is observed. The difference is about a factor of two, which agrees quite well with rigorous theoretical calculations[3].

Other, more complex colour coherence effects are seen in other types of event. For example, in collisions of particles other than electrons and positrons — such as quarks and antiquarks[4], or quarks and electrons — the colour fields of the initial particles can reinforce, or cancel, the colour fields of the particles produced.

As these patterns are mapped out, colour fields are becoming an ever more tangible aspect of reality. The recent accumulation of definitive results from a variety of experiments makes this an appropriate time to declare a triumph. ☐

Frank Wilczek is in the School of Natural Sciences, Institute for Advanced Study, Olden Lane, Princeton, New Jersey 08540, USA.
e-mail: wilczek@sns.ias.edu

---

1. Bartel, W. *et al. Z. Phys. C* **21,** 37–52 (1983).
2. The ALEPH collaboration *Phys. Rep.* **24,** 1–165 (1998).
3. Khoze, V. & Ochs, W. *Int. J. Mod. Phys. A* **12,** 2949–3120 (1997).
4. Abbot, B. *et al.* preprint hep-ex/9706012 on xxx.lanl.gov.

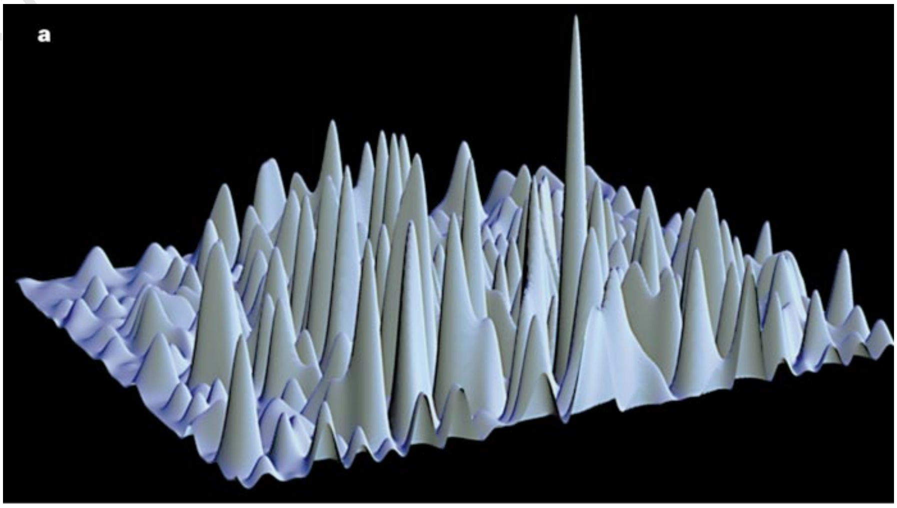
Photonics

Frozen light

Sajeev John

Electromagnetism is the fundamental mediator of all interactions in atomic physics and condensed-matter physics — in other words, the force that governs the structure of ordinary matter. It is rare to see an entirely new electromagnetic phenomenon, but Diederik Wiersma and colleagues report one on page 671 of this issue[1]. In carefully prepared semiconductor powders, Wiersma *et al.* have shown that light can be forced to stand still through the process of multiple scattering and wave interference. This experiment will lead to applications in optical data processing, spectroscopy and laser physics.

Our understanding and manipulation of electromagnetic waves has a long and rich history. The propagation of electromagnetic



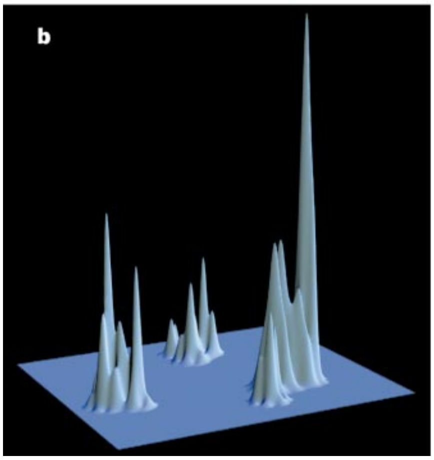


Figure 1 **A phase transition in light waves, from classical diffusion to localization.** a, **In classical diffusion through a scattering medium (such as white paint), the intensity distribution shows many fluctuations due to interference. Diffusion is possible because the peaks overlap.** b, **When the scattering becomes strong enough, the light is localized in separate peaks. The lack of spatial overlap between the peaks prohibits light transport.**

waves was predicted by James Clerk Maxwell in the nineteenth century, and Maxwell's equations are one of the pillars of modern physics. But the localization of light waves was predicted[2–4] only in the 1980s, and confirmatory experiments (first in the microwave spectrum[5,6], and now in the near-visible spectrum[1]) are milestones in our endeavour to create materials that mould the flow of light.

We all experience the effects of multiple scattering when it becomes dark on a cloudy day. Light from the Sun scatters many times from water droplets, following a tortuous diffusion path before reaching the ground. The distance that light travels within the cloud before being scattered into a random direction is called the mean free path. The effect of multiple light scattering is that the total amount of light transmitted through the cloud is reduced by a factor of the ratio of the cloud thickness to the transport mean free path. The rest comes back out of the other side, which is why clouds (and powders) look white.

Multiple scattering of light also takes place in human tissue. Here, the transport mean free path for infrared light of one micrometre wavelength is about a millimetre. Understanding the diffusive propagation of light in tissue is already paving the way to infrared imaging, a cheap and safe alternative to X-rays and nuclear magnetic resonance in diagnostic imaging of tumours[7].

But neither clouds nor human tissue can scatter light strongly enough to cause localization. To achieve that, Wiersma *et al.* slowly ground samples of the semiconductor gallium arsenide to create a fine powder with a high refractive index, which scatters light roughly a thousand times more strongly than tissue. In their experiment, the transport mean free path is about the size of the wavelength of light — a regime of scattering never before attained. In this regime, the photons no longer travel like billiard balls bouncing randomly through a maze. Instead, there are strong interference effects, due to the wave-like nature of the photon, which severely impede diffusion (Fig. 1). This becomes evident in the transmission properties of the medium: for grain sizes near the onset of localization, the transmission coefficient falls off as the square of the optical depth (the ratio of mean free path to sample thickness); and when localization occurs, transmission falls off exponentially.

Unlike electrons in a semiconductor, which are always conserved in number, photons are readily absorbed by matter. This complicates the interpretation of experiments, because absorption alone can lead to exponential decay of the transmitted light intensity. In order to separate the effects of absorption from true localization, Wiersma *et al.*[1] varied the temperature of their semiconductor powders over a range of about 500 K. This leads to characteristic variations in the wavelength of the material's optical absorption edge, allowing localization and absorption to be distinguished. To further confirm that wave interference causes the localization transition, the authors compared their results with coherent back-scattering experiments[8,9] on the same samples, which directly measure the interference between time-reversed optical paths.

The history of light localization has unfolded in a manner that is almost the reverse of electron ('Anderson') localization. In the case of electrons, the invention of the semiconductor preceded considerations of localization. In the case of photons, considerations of localization are a driving force in the development of photonic band-gap materials[10,11], the photonic analogue of the semiconductor. These materials consist of a periodic array of scatterers with a lattice constant comparable to the wavelength of light. Photonic band-gap materials have important technological applications — in the development of micro-lasers and optical transistors, for example — because they can coherently localize light when disorder is introduced (either by structural defects or by doping the material with resonant atoms or molecules).

Powders are much easier to make than photonic band-gap materials, and the localization length in a powder is much longer: the photon may propagate hundreds of wavelengths before realizing that it is completely trapped. That may be very useful for cooperative effects involving photons and atoms, such as laser action.

Further progress in the field of light localization will depend on the optical purity of the materials. Optical fibres with an extinction length of many kilometres are now quite routine. But unlike optical fibres, which have a refractive index of about 1.5, materials that localize light must have a refractive index of at least 3.0, and at the same time be optically pure. (Unfortunately, a high index usually means operating close to a resonance, and absorption also becomes large near a resonance.) Candidates include silicon and germanium, either powdered or in the ordered form of a photonic band-gap material. These developments bring closer the new age of photonics, in which zero-threshold micro-lasers, sub-picosecond optical switches and all-optical transistors will take over from conventional electronics. ☐

Sajeev John is in the Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7.
e-mail: john@physics.utoronto.ca

1. Wiersma, D., Bartolini, P., Lagendijk, A. & Righini, R. *Nature* **390,** 671–673 (1997).
2. John, S. *Phys. Rev. Lett.* **53,** 2169–2173 (1984).
3. Anderson, P. W. *Phil. Mag. B* **52,** 505–509 (1985).
4. John, S. *Phys. Today* **44,** 32–40 (1991).
5. Genack, A. Z. & Garcia, N. *Phys. Rev. Lett.* **66,** 2064–2068 (1991).
6. Garcia, N. & Genack, A. Z. *Phys. Rev. Lett.* **66,** 1850–1854 (1991).
7. Yodh, A. & Chance, B. *Phys. Today* **48,** 34–40 (1995).
8. van Albada, M. P. & Lagendijk, A. *Phys. Rev. Lett.* **55,** 2692–2696 (1985).
9. Wolf, P. E. & Maret, G. *Phys. Rev. Lett.* **55,** 2696–2700 (1985).
10. Yablonovitch, E. *Phys. Rev. Lett.* **59,** 2059–2063 (1987).
11. John, S. *Phys. Rev. Lett.* **59,** 2486–2490 (1987).

Spongiform encephalopathies

B lymphocytes and neuroinvasion

Paul Brown

The latest episode in the long-running serial of scrapie pathogenesis appears on page 687 of this issue[1], with a further molecular dissection of genetically altered mice. The Swiss team[1] has taken advantage of the fact that the gene encoding the prion protein PrP — the leading candidate for the cause of all transmissible spongiform encephalopathies, including scrapie and Creutzfeldt–Jakob disease (CJD) — can be made inoperative (that is, 'null'), without evident harm to the mice[2]. Working backwards from the target organ of disease (the brain) to peripheral (intraocular, intravenous or intraperitoneal) sites of infection, the authors have used surgical transplants in combination with normal and genetically altered mice in an effort to decode the pathogenesis of disease at the molecular level. They show that differentiated B lymphocytes are important for neuroinvasion — a finding with both public-health and therapeutic implications.

Intracerebral inoculation of the scrapie agent into a null mouse does not produce disease. However, intracerebral inoculation of a null mouse harbouring a small, PrP-expressing neural transplant destroys the graft, although the surrounding tissue is free from disease. In contrast, inoculation by peripheral routes does not destroy the graft: intraocular inoculation fails despite the fact that, in normal animals, the optic nerve is an efficient route of brain infection; and intraperitoneal or intravenous inoculation do not destroy the graft, even after lethal irradiation and transplantation of PrP-expressing haematopoietic stem cells (although these mice do develop infection of the spleen).