(Fig. 2). A quantum computer contains a large number of qubits, which need to be interconnected for certain quantum operations. In addition, it will be necessary to address and manipulate every single qubit. These aspects will be the challenging objectives of the coming years.

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GRAPHENE

Phonons behaving badly

Raman spectroscopy experiments show that the interaction between electrons and phonons in graphene resembles the Dirac fermion–photon coupling in quantum electrodynamics.

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When graphene, a one-atom-thick crystal of carbon, was first isolated in 2004, using adhesive tape applied to graphite[1], it did not attract a lot of attention. However, after the observation of an unusual relativistic quantum Hall effect in this material in 2005[2,3], the interest and amount of literature from the physics community grew exponentially[4]. What the 2005 experiments showed unequivocally is that the elementary electronic excitations in this material can be described in terms of two-dimensional Dirac fermions, that is, charge carriers that have lost their rest mass and move with a velocity 300 times slower than the speed of light (Fig. 1). In other words, the electrons can be considered as relativistic particles but with a strongly reduced speed of light. Writing on page 198 of this issue, Pisana *et al.* uncover another experimental effect linked to the unusual properties of graphene[5]. They show that the interaction between Dirac fermions and lattice vibrations in graphene cannot be described as for usual metals, and resemble instead the interaction between relativistic electrons and light described by quantum electrodynamics (QED).

The connections between electron transport in graphene and QED are indeed quite strong[6]. In QED, which applies to vacuum, the interaction between light quanta, or photons, and Dirac fermions is very strong. Photon propagation is accompanied by processes of subsequent creation and annihilation of fermions and their antiparticles. Dirac fermions and photons are said to be coupled, that is, one cannot be treated individually and independently from the other. In the case of graphene, the strictly two-dimensional character of the carbon crystal introduces a strong asymmetry between the motion of Dirac fermions, restricted to the plane, and that of photons that propagate in the three-dimensional space. The coupling is therefore very weak, and photons can be seen only as a perturbation that affects slightly the velocity of the Dirac fermions[7]. However, in graphene the presence of the carbon nuclei provides other bosonic particles that can interact with the fermions, namely the quanta of atomic vibrations or phonons. Because phonons cannot exist outside the two-dimensional crystal, they can couple quite strongly with the Dirac fermions, in exactly the same way two-dimensional photons would[8]. In this regard, Dirac fermions and phonons interact in a two-dimensional QED, that is, phonons can be considered graphene's new photons.

In the early days of quantum mechanics, in their studies of the spectra of molecules, Robert Oppenheimer and Max Born discovered that a major simplification in the calculations could be made because of the large difference between the masses of electrons and nuclei. This simplification relied on the fact that electrons, being much lighter, are much faster than the nuclei. The Born–Oppenheimer approximation is

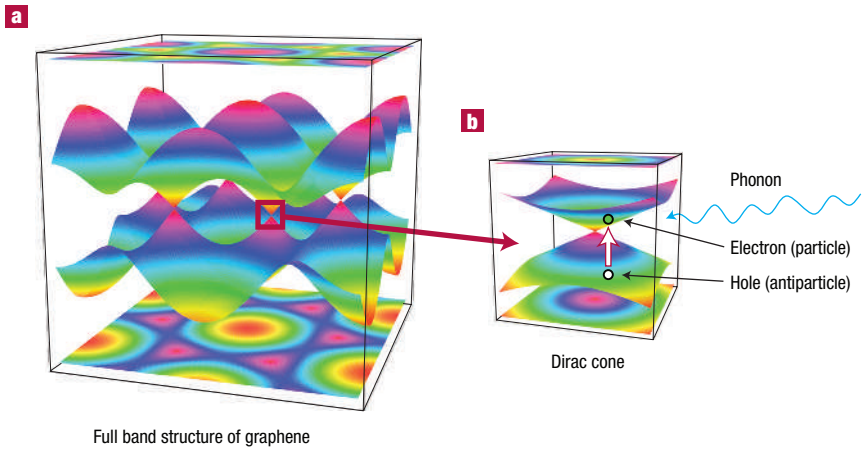

Figure 1 Band structure of graphene and its projection in the momentum space. **a**, The full band structure. **b**, Magnification around the vertex of the Dirac cone (Dirac point). By absorbing a phonon an electron is excited from the lower cone to the upper cone leaving a hole (antiparticle) behind. In particle physics this is called pair-creation process.

one of the starting points for the study of a large class of systems, ranging from molecules to crystalline solids, because it permits a clear separation of energy scales, allowing for the study of electrons and phonons individually. In addition, in ordinary metals, where non-relativistic electrons and phonons propagate, the Born–Oppenheimer approximation is supplemented by an extra factor, namely, that the electron response to an electric field is so fast that the response to the phonon motion is adiabatic, that is, can be computed as if at any time the positions of the nuclei were frozen.

Pisana and co-authors have used Raman spectroscopy to study the electron–phonon interaction, and in particular the phonon response to the application of an electric field perpendicular to the graphene crystal. They show that, unlike in ordinary metals and semiconductors where electrons are described by non-relativistic quantum mechanics, the phonon energy changes in an unusual way with the applied field, in agreement with earlier theoretical predictions[8,9] and experiments by other groups[10]. Most importantly, the behaviour observed in these experiments shows that graphene violates the adiabatic Born–Oppenheimer approximation.

To understand the origin of this anomalous observation we have to recall the similarity between phonons in graphene and photons in QED. In graphene, phonon propagation is linked to the creation of electron–hole couples. But a hole is simply the electron antiparticle (Fig. 1b), which makes the analogy with QED almost perfect. Because the phonon propagation is so strongly connected to complex processes involving electrons, the adiabatic Born–Oppenheimer approximation — which is based on separating the motions of electrons and phonons, and consider these as frozen — cannot be valid.

The experimental observation of the strong electron–phonon coupling in graphene is not just another demonstration of the analogy with QED, and suggests that other interesting phenomena may be observed. For example, the strong electron–phonon interaction in metals is related to the emergence of superconductivity, which indicates that even in graphene this phenomenon could occur. Despite the fact that no evidence has so far been reported of graphene superconducting, it is possible that it is on the verge of a superconducting instability, and with a slight modification, either structural or chemical, a two-dimensional graphene superconductor might be obtained. Only time and new experiments will tell whether superconductivity is really possible in this intriguing material.

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PHOTONIC CRYSTALS

A view of the future

Despite intense research efforts, no three-dimensional materials with a photonic bandgap for visible wavelengths have yet been fabricated. A new self-assembly strategy lays out the route towards the realization of this dream.

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It is nearly twenty years since the possibility of materials with a photonic bandgap — where light of certain wavelengths is forbidden to propagate in any direction — was first discussed[1,2]. This idea has spawned the field of photonic crystals, which allows us to manipulate light in new and amazing ways. However, the original goal, a three-dimensional material with a complete photonic bandgap for visible light, has eluded us. Such a prolonged challenge often promotes creative solutions, and on page 202 of this issue[3], Hynninen *et al.* propose a new route towards this aim. Their plan uses recent advances in the self-assembly of colloidal particles into beautifully complex crystal structures. If realized, their approach may finally allow us to see a photonic bandgap with our own eyes.

In 1987, it was well known that materials that were periodically structured on a scale comparable to the wavelength of light could prohibit photons from travelling in specific directions. Inside such a structure, reflections from the periodic interfaces can cause constructive and destructive interference. A common use of this effect is for anti-reflection coatings. However, the question was whether an artificial material could forbid light from travelling in all directions simultaneously. If this occurred, a range of wavelengths, or bandgap, could be created where travelling electromagnetic waves would not be allowed to exist inside the material. Because fundamental optical properties such as fluorescence rely on such waves, interesting implications follow from their absence.

But what is needed to obtain a photonic bandgap for visible wavelengths? Essentially, destructive interference must occur for all propagation directions. This requires a crystal from 'atoms' with a size similar to the optical wavelength, which for the visible is several hundred nanometres. In addition, the waves must reflect strongly from these 'atoms', a property determined by their index of refraction. If the refractive index could be arbitrarily high, a photonic bandgap could exist in any three-dimensional crystal. Unfortunately, we are constrained by the materials that nature provides. Because high-refractive-index materials are more readily available at longer wavelengths, several approaches have created photonic bandgaps for the near infrared[4–8]. For visible wavelengths, the highest available