GRAPHENE

The running of the constants

To first approximation, the dispersion relation around the Fermi energy of single-layer graphene is linear, making its charge carriers behave like massless relativistic subatomic particles. More careful inspection of its low-energy band structure suggests the picture is more complex, extending the analogy even further.

Maria A. H. Vozmediano

The best times in Physics are those when physicists of different expertise meet around a problem of common interest. And this is now happening in the case of graphene. From the early days of the isolation of single sheets of graphene, the relativistic nature of its charge carriers was clear[1]. These carriers, known as Dirac fermions, are described by equations similar to those that describe the quantum electrodynamic (QED) interactions of relativistic charged particles. A meticulous study performed by Elias and co-workers[2] of the electronic structure of graphene shows that at very low energies reaching a few meV of graphene's Dirac point, where its cone-like valence and conduction bands touch, the shape of the conduction and valence bands diverge from a simple linear relation. The result implies that the analogy between graphene and high-energy physics is deeper than first expected. In particular, it implies that the electromagnetic coupling of graphene does renormalize, as occurs in quantum field theory.

The magnitude of the coupling constants that characterize the strengths of the fundamental forces of nature vary profoundly. Between gravity, the weakest force, and the strong force, the strongest, the difference is a mind-bending 40 orders of magnitude. Between these extremes, electromagnetism governs essentially all the interactions between atoms and molecules and determines the behaviour of everyday condensed matter systems like graphene. Despite the name, coupling constants are not in fact constant, but can change depending on the energy scale of the experiments in which they are measured. For instance, the fine structure constant of QED (α_{QED}) is approximately 1/137 in experiments performed at energies of the order of electron mass (about 0.5 MeV), but is found to increase to approximately 1/128 in experiments carried out at the much higher energy of around 90 GeV in the Large Electron–Positron collider (LEP) at CERN. This so-called running of coupling constants is a consequence of quantum field theory and is related to renormalization — the solution to the 'divergence problem' and the infinities that arise when computing physical properties in perturbation theory (see Fig. 1).

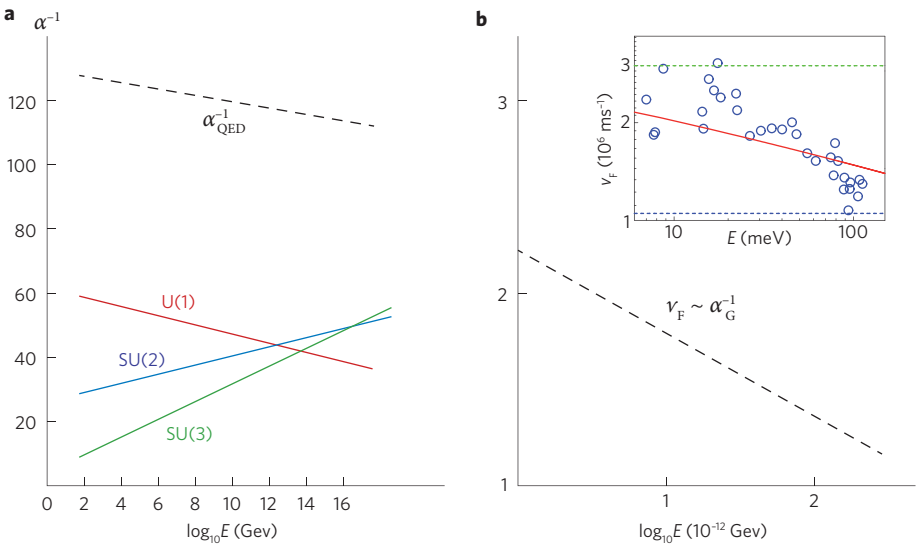


Figure 1 | Initial formulations of quantum field theory predicted infinite values of basic physical quantities when calculated with perturbative techniques. This 'divergence problem' is solved by renormalization of the coupling constants. **a**, Typical picture of the running of the inverse of the coupling constants (α^{-1}) as a function of energy scale (E) in the standard model SU(3)×SU(2)×U(1) of elementary particles, and QED (α_{QED}). **b**, The running of the Fermi velocity in graphene is directly proportional to the inverse coupling constant. The horizontal axis represents the log of the energy in meV. The inset shows a plot of the actual measurement with error bars represented by the radius of the circles. The steeper slope of graphene with respect to the QED case is a result of the larger value of the coupling constant in graphene.

One of the most notable things discovered about graphene when it was first isolated was the linear shape of its conduction and valence bands[1]. This implies that its electrons move as if they are free of mass. But what does all this really mean? QED describes free electrons moving through a vacuum and interacting with other charged particles by the exchange of photons with a strength given by α_{QED}. The Dirac fermions of graphene are not real electrons in the strictest sense of the word, but collective degrees of freedom that just happen to have the same charge and spin as electrons. They are an effective description produced from the free remainders of the carbon orbitals in the graphene's honeycomb lattice. It is a surprising and happy coincidence that they do behave as free electrons in most respects.

The experiment carried out by Elias *et al.* push the analogy to its limits. The coupling constant in QED is defined as a function of the fundamental electron charge, e, and the speed of light, c, by $\alpha_{QED}=e^2/4\pi c$. In graphene, c is replaced by the Fermi velocity, v_F, which is of the order of $c/300$. This increases the effective fine structure constant in graphene by the same amount, so that $\alpha_G \approx 300\alpha_{QED}$. The running of this constant in QED is due to the renormalization of the electron charge and c remains constant. The increase in α_{QED} at higher energies has been demonstrated in accelerators in the energy range from 1 MeV to 100 GeV. In contrast, in the case of graphene, the electric

charge stays constant and the upward renormalization of α_G is due to a decreasing Fermi velocity at increasing energies. In both QED and graphene, the renormalization of the coupling between two different energies E_1 and E_2 is given by the relation

$$\alpha(E_2)=\frac{\alpha(E_1)}{1-A\alpha(E_1)\ln(E_2/E_1)}$$

where A is a constant that depends on the number of fermion species that contribute to the renormalization at energy E_2.

The idea that such a renormalization would occur in graphene was suggested almost a decade before it had actually been successfully isolated[3]. The reason it has taken so long since graphene's initial isolation to confirm it experimentally is that it only becomes evident within 1 eV of the Dirac point and a clear demonstration of the validity of any logarithmic relation naturally requires a dataset that spans several orders of magnitude. In this sense, the experiments performed by Elias *et al.* represent a real tour-de-force, probing graphene's electronic structure down to fractions of meV of the Dirac point, and confirming the logarithmic behaviour all the way down to this point. Beyond establishing the QED-like behaviour of graphene further than any physicist might have reasonably expected, the result improves our understanding of the often controversial nature of electron–electron interactions in neutral graphene.

Maria A. H. Vozmediano is at the Instituto de Ciencia de Materiales de Madrid (CSIC), Sor Juana Inés de la Cruz 3, Madrid 28049, Spain.
e-mail: vozmediano@icmm.csic.es

References
1. Novoselov, K. S. *et al. Nature* **438,** 197–200 (2005).
2. Elias, D. C. *et al. Nature Phys.* **7,** 701–704 (2011).
3. González, J., Guinea, F. & Vozmediano, M. A. H. *Nucl. Phys. B* **424,** 595–618 (1994).

Published online: 24 July 2011

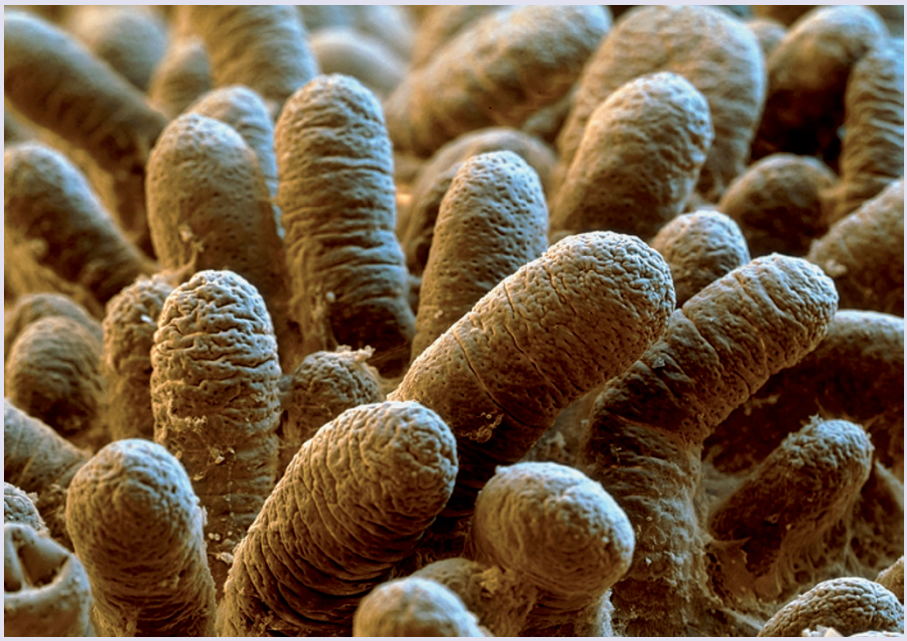
BIOPHYSICS

On mechanics and morphology

When D'Arcy Thompson penned his 1917 book *On Growth and Form* he boldly declared that the morphologist — devoted to understanding the structure of organisms — is *ipso facto* a student of physical science. His meaning was clear: the growth of complex structures mediating specific biological function is underpinned by an intrinsic mechanics, an appreciation of which is crucial to a broader understanding of both form and function.

Thierry Savin and colleagues refer to Thompson's tome in their investigation, published in *Nature*, of the elaborate looped morphology that arises in the vertebrate gut (*Nature* **476,** 57–62; 2011). Using experiment, simulation, and an innovative physical mock-up comprising rubber tubing stitched to latex, they have examined the forces arising from relative growth between the gut tube and a neighbouring sheet of tissue known as the dorsal mesentery. The study reveals a mechanism for the formation of loops based on differential strain between the two tissues.

This is a timely nod to Thompson's century-old ideas, given the recent surge of physicists and mathematicians into the biological sciences, problem-solving artillery engaged. In another paper, published in *Physical Review Letters*, Edouard Hannezo, Jacques Prost and Jean-François Joanny adopt a similarly mechanical approach to understanding the complex structures seen lining the small intestine (pictured), invoking an analogy with the buckling of metallic plates under compression (*Phys. Rev. Lett.* **107,** 078104; 2011). They have developed a model that implicates cellular division and death as sources of internal stress, which in turn influences morphology and induces mechanical feedback on organ and tissue development.



© SPL

One of the most interesting aspects of Thompson's treatise is an emphasis on the degree to which structures in different tissues and organisms can be related to one another by means of mathematical transformation. Both of the new papers offer striking evidence to this effect. For Savin *et al.*, scaling arguments for the size, number and radius of loops account for qualitative and quantitative variation across different species, including chick, quail, finch and mouse. In a similar spirit, Hannezo and colleagues report that by tuning their model for the morphology of the small intestine, the markedly different structures populating the colon can also be reproduced.

The upshot of this and related work is that macroscopic mechanics drives morphology during the formation of tissues and organisms — bringing the formalism of physics to bear on long-standing problems in developmental biology.

ABIGAIL KLOPPER

MAGNETIC ORDER

Surfaces get hairy

Surfaces inherently lack inversion symmetry. This property is now shown to promote the spontaneous formation of a lattice of spin vortices in a thin magnetic film, a finding that suggests a simple route towards new spintronics applications.

Christian Pfleiderer

It is well established that you can't comb a hairy sphere flat without creating a whorl. But for magnetically ordered materials it seems at least plausible that the spins can be gradually rotated until they are parallel, just like combed hair, without having to deal with vortices or whorls. However, writing in *Nature Physics*, Stefan Heinze and colleagues[1] report a form of magnetic order in a mono-atomic magnetic film that consists of a lattice of vortices that cannot be removed by gradual rotations of the spins. A key ingredient that gives rise to these vortices is the lack of inversion symmetry of the surface supporting the film. Heinze *et al.* thus identify a very simple route to magnetic vortices and vortex lattices, which, in turn, may be expected to occur in a large number of different systems.

The reason physicists get excited about hairy spheres and the whorls they support (or have to support) has to do with the topology of such objects. Interest in spheres with a hairy surface has a long tradition, as topologically distinct whorls and vortices were repeatedly considered by different scientists to provide possible answers to some of the most pressing scientific challenges of the time. For instance, in the nineteenth century, Lord Kelvin attempted to describe atoms in terms of vortices. And in the 1950s, Werner Heisenberg attempted to explain the existence of particles in a framework of topologically stable whirls of continuous fields. Both failed, but, in the 1960s, the English particle physicist Tony Skyrme, inspired by Heisenberg's attempt, successfully explained neutrons and protons in terms of whorls of pion fields[2]. Skyrme's success came as a surprise, for protons and neutrons are fermions (that is, their wavefunction changes sign whenever two of them are exchanged), whereas pions are bosons (and so their wavefunction does not change sign when two of them are exchanged).

In recognition of Skyrme's accomplishments, particle-like states of continuous fields in nuclear matter, quantum Hall systems, liquid crystals or ultracold atoms are now generally referred to as skyrmions[3]. In all of these examples, the non-linear interactions at the heart of the skyrmions differ. Yet, all of these skyrmions are alike in terms of their topology. The original skyrmion as devised by Skyrme may be viewed as a hairy sphere (or a hedgehog), with arrows pointing outwards (Fig. 1a). When these arrows are gradually rotated, their topology remains unchanged (Fig. 1b). A stereographic projection from three to two dimensions establishes a vortex (Fig. 1c) that is topologically equivalent to the hairy sphere (Fig. 1a). In other words, the vortex seen in Fig. 1c is a two-dimensional skyrmion. When directly performing the stereographic projection of the hairy sphere shown in Fig. 1a, we obtain the type of cycloidal vortices identified experimentally by Heinze *et al.*[1]

Skyrmions like those shown in Fig.1c were recently observed in neutron-scattering[4,5] and transmission-electron-microscopy[6,7] experiments on bulk samples. These were the first observations of skyrmions in magnetic materials, and in fact were the first time that skyrmions were imaged microscopically at all. The non-linear interaction driving the skyrmions in bulk materials originates from the lack of inversion symmetry of their crystal structures, which causes a special form of spin–orbit coupling, known as the Dzyaloshinsky–Moriya interaction. Although there are many bulk compounds with a non-centrosymmetric crystal structure that may, in principle, support skyrmions, the perhaps most interesting cases — with a view to applications — are surfaces, which inherently lack inversion symmetry. Surprisingly, the importance of the same Dzyaloshinsky–Moriya interactions as in bulk compounds, but entirely due to the asymmetry of surfaces supporting thin magnetic films, was demonstrated only a few years ago in an experimental study of a monoatomic layer of manganese on a tungsten substrate[8]. This paved the way for the study of Heinze *et al.*[1]

To identify the skyrmion lattice in a thin magnetic film, Heinze *et al.* chose to revisit their earlier studies of a mono-atomic layer of iron on an iridium substrate[9]. As their experimental probe, they used spin-sensitive scanning tunnelling microscopy, where the tunnelling current depends sensitively on the spin-polarization of the surface. However, in comparison to bulk materials, the interactions causing the skyrmion lattice in the thin iron films studied by Heinze *et al.* are more complex and reflect a combination of different mechanisms. Again, Dzyaloshinsky–Moriya-type interactions are a key ingredient, but equally important is a four-spin exchange interaction, which, curiously, shares certain similarities with the interactions originally considered by Skyrme to describe particle-like states of pion fields. The identification of the spin structure of the iron film reported by Heinze *et al.* is therefore quite involved, requiring state-of-the-art electronic-structure calculations — and a good deal of intuition.

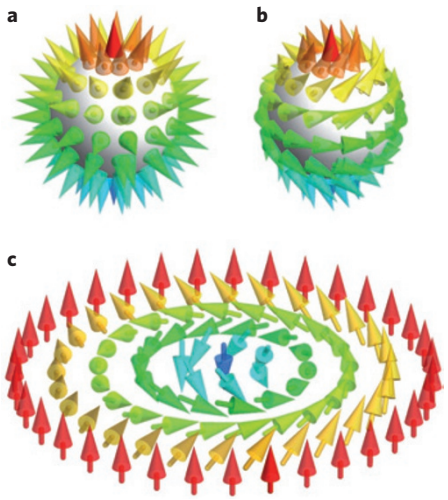


Figure 1 | Topological equivalence of a hairy sphere and a vortex. After combing a hairy sphere (**a**, **b**) a stereographic projection onto the plane results in a vortex (**c**). The hairy sphere and the vortex are topologically equivalent; both are skyrmions. Image courtesy of Achim Rosch.

The second important difference to the skyrmions in bulk magnets and the other examples listed above concerns the size of the magnetic unit cell in the experiments of Heinze *et al.*[1], which is very small, involving a few magnetic moments only. At first sight, describing the magnetization in terms of a continuous field seems, therefore, an unjustified assumption. It turns out, however, that the concepts of topology can be applied also for small numbers of local moments (see, for example, ref. 10 and references therein).

The third difference, and perhaps the most important, is that the skyrmions in the iron films form spontaneously, whereas the skyrmions in bulk compounds must be stabilized by a small magnetic field. This is in contrast with the older understanding of skyrmions as an excitation rather than a ground-state property.

Thin magnetic films lend themselves, quite naturally, to applications, and it is therefore tempting to speculate briefly on the technical potential of the results reported by Heinze *et al.*[1] One direction of investigation that comes to mind could exploit the tiny size and topological stability of the skyrmions to increase the packing density of magnetic recording media. Another possibility is to explore the recent discovery of spin-transfer torques at ultra-low current densities in the skyrmion lattices in bulk compounds[11] in suitably designed thin magnetic films on an insulating substrate. Without doubt, Heinze *et al.* have pushed the door wide open for an entirely new generation of very elegant and extremely simple spintronics applications. ❐

Christian Pfleiderer is at the Lehrstuhl für Experimentalphysik E21, Technische Universität München, D-85748 Garching, Germany.
e-mail: christian.pfleiderer@frm2.tum.de

References

1. Heinze, S. *et al. Nature Phys.* **7,** 713–718 (2011).
2. Skyrme, T. H. R. *Nucl. Phys.* **31,** 556–569 (1962).
3. Brown, G. E. & Rho, M. (eds) *The Multifaceted Skyrmion* (World Scientific, 2010).
4. Mühlbauer, S. *et al., Science* **323,** 915–919 (2009).
5. Münzer, W. *et al. Phys. Rev. B* **81,** 041203 (2010).
6. Yu, X. Z. *et al. Nature* **465,** 901–904 (2010).
7. Yu, X. Z. *et al. Nature Mater.* **10,** 106–109 (2011).
8. Bode, M. *et al. Nature* **447,** 190–193 (2007).
9. von Bergmann, K. *et al. Phys. Rev. Lett.* **96,** 167203 (2006).
10. Nagaosa, N., Sinova, J., Onoda, S., MacDonald, A. H. & Ong, N. P. *Rev. Mod. Phys.* **82,** 1539–1592 (2010).
11. Jonietz, F. *et al. Science* **330,** 1648–1651 (2010).

CUPRATE SUPERCONDUCTIVITY

Magnetic fluctuations revealed

A comprehensive map of the spin fluctuations in high-temperature superconductors is emerging through the application of a novel experimental technique — and the surprising results are challenging theorists.

Matthias Vojta

Neutron scattering is the key experimental technique when it comes to determining the momentum-space structure of magnetic order and magnetic excitations in solids. Using the measurable change in energy and momentum of an inelastically scattered neutron, the intensity and dispersion relation of the solid's excitation (which caused the scattering) can be mapped out. Applied to superconducting copper oxides, neutron scattering has revealed[1] the existence of antiferromagnetic fluctuations that seem to be short-range, short-lived remnants of the static antiferromagnetism found in the insulating parent compounds.

However, the observed excitations were restricted to a narrow window in both energy and momentum and furthermore carried relatively little spectral weight, posing a challenge to theoretical ideas about magnetic fluctuations being the source of Cooper pairing in these superconductors. Some researchers have suggested that the experimental limitations inherent in neutron scattering were partially responsible for this state of affairs — and only now has a breakthrough occurred.

In *Nature Physics*, Le Tacon and colleagues[2] report the application to various copper oxides of an alternative technique to map magnetic excitations: resonant inelastic X-ray scattering (RIXS)[3]. Here, an electron is transferred, by a high-energy photon, from a deep core level into an unoccupied low-energy state; subsequently, an electron from a different low-energy state fills the core hole and emits a high-energy photon. Thus, a net excitation is generated in a low-energy band, the energy and momentum of which can be measured by examining the scattered photon.

Among the advantages of RIXS, compared with neutron scattering, is the large cross-section for the scattering of photons (which eliminates the need for large samples) and the possibility to probe essentially the entire Brillouin zone. There are disadvantages as well: in contrast to neutron scattering, the cross-section is not simply related to a dynamic susceptibility, which complicates the data analysis, and the energy resolution is at present limited to about 100 meV (it's far below 1 meV in state-of-the-art neutron-scattering experiments). Despite these limitations, the past decade has seen exciting progress in RIXS[3] such that investigations of elementary spin excitations have now become feasible.

Le Tacon *et al.*[2] have investigated magnetic excitations using RIXS in a family of copper-oxide materials, covering a range of hole

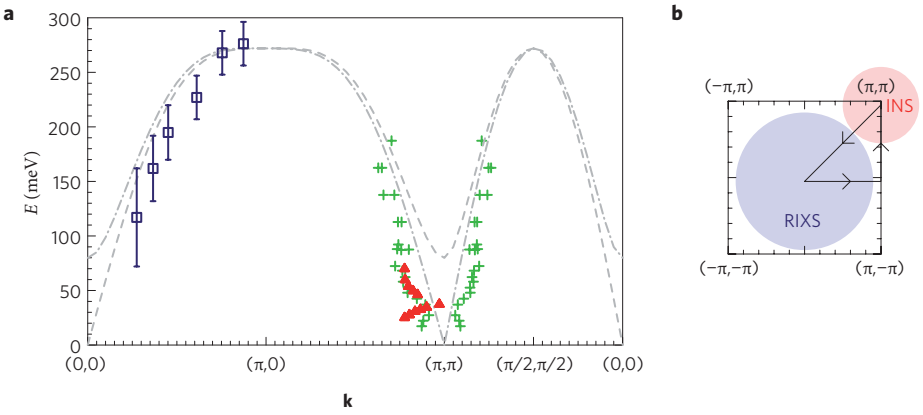


Figure 1 | Dispersion of magnetic excitations in energy–momentum (E-**k**) space for $YBa_2Cu_3O_{6+x}$ copper oxides. **a**, The RIXS data of Le Tacon *et al.*[2] (blue squares) together with inelastic neutron-scattering (INS) results[8] (red triangles, assuming 100 and 010 directions to be equivalent), both for $YBa_2Cu_3O_{6.6}$. Also shown are high-energy INS data[9] for $YBa_2Cu_3O_{6.5}$ (green crosses; the dispersion was found to be approximately isotropic around (π, π)). The lines show the dispersion of acoustical and optical spin-wave modes, representing the excitations of the undoped parent compound, obtained from a bilayer Heisenberg model. **b**, Two-dimensional Brillouin zone, showing the momentum-space path for the data in **a**, and the regions in momentum space where RIXS and INS are effective.

dopings from the undoped insulator to the slightly overdoped superconductor. In all doped materials, they identified damped spin excitations with high intensity over a large part of momentum space. These excitations, in both their overall dispersion and their intensity, seem to show surprisingly little variation with doping.

These findings are important for a number of reasons. First, together with similar recent experiments[3–5], they establish RIXS as a powerful tool for the investigation of complex correlated-electron materials. Second, they show that previous neutron-scattering studies have indeed missed a significant part of the spectral weight of spin fluctuations in copper oxides. This implies that theories of electron pairing based on the exchange of magnetic fluctuations can be considered on safer ground. In fact, Le Tacon *et al.* provide a sample calculation of a superconducting critical temperature (T_c), in which they use the measured spin-fluctuation spectrum and electronic bands as input and obtain a T_c value comparable to the experimental one.

Third, and perhaps most importantly, their data indicate that key features of the spin fluctuations in doped copper oxides are strikingly similar to that of their undoped counterparts (Fig. 1): at the elevated energies probed by RIXS, the only significant effect of doping is an energy broadening of the excitations, probably arising from damping due to electron-hole excitations. (One should note that the present energy resolution of RIXS is insufficient to resolve fine structures on scales below 100 meV; therefore the similarity of doped and undoped spectra refers to gross features, and the details may well differ.)

Given the fact that the excitations in the undoped parent compounds are well described in terms of spin waves of a local-moment antiferromagnet, the data reinforce one of the key questions about copper oxides: is the magnetism of these superconductors better understood in an itinerant or in a local-moment picture?[6] This is related to a second unanswered question, which is of a fundamental nature: is the weakly doped Mott insulator a Fermi liquid, or a more exotic metallic state coexisting with local moments?[6,7]

The data provided by Le Tacon and colleagues[2] indicate that a local-moment picture accounts for the observed spin excitations at elevated energies even up to optimal doping. This then suggests that the underlying metallic state is either not a Fermi liquid, or that Fermi-liquid behaviour is restricted to very small energies — a conclusion consistent with both transport and photoemission data. In such a situation, employing Fermi-liquid based theoretical methods can give only indicative results at best — this applies, for example, to the Eliashberg calculation of the critical temperature performed by Le Tacon *et al.*[2]. Unfortunately, neither a phenomenological understanding nor an efficient theoretical description of the relevant non-Fermi liquid regime is available so far. These hold the key to further progress in the field. ❐

Matthias Vojta is at the Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden, Germany.
e-mail: matthias.vojta@tu-dresden.de

References

1. Birgeneau, R. J. *et al. J. Phys. Soc. Jpn* **75,** 111003 (2006).
2. Le Tacon, M. *et al. Nature Phys.* **7,** 725–730 (2011).
3. Ament, L. J. P. *et al. Rev. Mod. Phys.* **83,** 705–767 (2011).
4. Braicovich, L. *et al. Phys. Rev. Lett.* **102,** 167401 (2009).
5. Braicovich, L. *et al. Phys. Rev. Lett.* **104,** 077002 (2010).
6. Vojta, M. *Nature Phys.* **5,** 623–624 (2009).
7. Lee, P. A., Nagaosa, N. & Wen, X.-G. *Rev. Mod. Phys.* **78,** 17–85 (2006).
8. Hinkov, V. *et al. Nature Phys.* **3,** 780–785 (2007).
9. Stock, C. *et al. Phys. Rev. B* **82,** 174505 (2010).

NONLINEAR X-RAY OPTICS

The next phase for X-rays

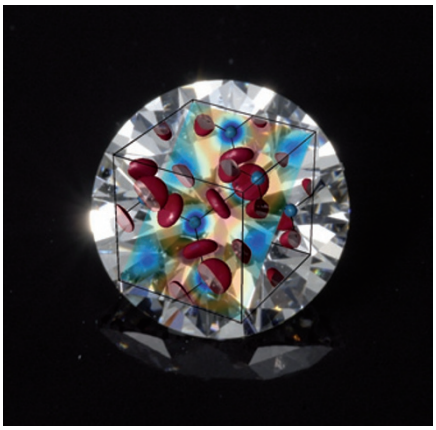
Phase information can be obtained from inelastically scattered X-rays by combining parametric down-conversion with tunable quantum interference. This is a step towards putting this nonlinear phenomenon to a practical use in the X-ray regime: investigating the optical response of chemical bonds at their electron-volt and subnanometre scales.

Bernhard Adams

Parametric down-conversion is a quantum-optical process in which a 'pump' photon splits spontaneously into two (the 'signal' and 'idler') in a nonlinear optical medium. Although X-ray parametric down-conversion (XPDC) has made occasional appearances in the scientific literature, it has not enjoyed the same popularity as its cousin, 'visible-light' parametric down-conversion. The latter is used routinely as a source of entangled photons of infrared/visible/ultraviolet light for quantum cryptography and computation. The reasons for the relative obscurity of XPDC are twofold: experiments are difficult to do, requiring months of patience at an X-ray tube[1] or days on a synchrotron-radiation source[2,3], and its application to the resolution of a burning scientific or technical question has been lacking so far. Now, writing in *Nature Physics*[4], Kenji Tamasaku and his colleagues report an experiment that could eventually lead to a spectroscopic application of XPDC by realizing an idea first discussed 30 years ago[5].

In parametric down-conversion the energies of the signal and the idler add up to that of the pump, and momentum conservation usually involves a momentum transfer to the converter medium. In the present work this momentum transfer provides the spatial resolution associated with a nonlinear X-ray scattering process. Unlike in most other XPDC experiments, the splitting here is highly asymmetric with the signal photon in the X-ray wavelength regime and the idler in the deep ultraviolet (100 eV).

This combination of relatively low energies (10–100 eV) and large momenta that are characteristic of X-ray scattering opens the possibility of probing the optical response of chemical bonds at their natural energy and length scales, that is electron volt and subnanometre, respectively. This, of course, is



COURTESY OF KENJI TAMASAKU

XPDC imaging. Tamasaku *et al.*[4] use their parametric down-conversion-based technique to investigate the response of diamond to ultraviolet light at a resolution as small as 0.54 Å.

what traditional inelastic X-ray scattering is all about. The difference here, however, is that the process involves the quantum interference of two pathways that lead to the same final state. Both XPDC followed by photoabsorption of the idler photon, and inelastic X-ray, or Compton, scattering result in a signal/Compton-scattered photon of reduced energy and an electron that carries the energy balance as kinetic and potential energy. The interference between these two pathways can be modulated (see Fig. 1 of ref. 1) by using the differing dispersion relations of the two contributions: whereas the energy-splitting ratio of XPDC depends strongly on the angular detuning from the Bragg diffraction condition, the energy loss in inelastic X-ray scattering goes rather gradually with the scattering angle.

This tuning capability can be used, in principle, to obtain the phase information that is normally lacking in a scattering experiment where only intensities are recorded. Here, the amplitude of the inelastic X-ray scattering can be considered a phase-constant reference while the idler photon energy from the XPDC process is tuned through the energy bandpass of the X-ray photon-energy analyser. This can be done for different analyser settings to probe resonances in the sample.

To recover the linear optical susceptibility of the material from the nonlinear optical XPDC process, one has to know the relationship between the two. A model based on oscillators with poles far away in frequency[6] may suffice at energies far above the valence structure of the material. However, matters become much more complicated as frequencies approach those of the band structure of the material (that is, idler photon energies in the range 0–20 eV). The method should remain valid, in principle, but data analysis becomes much harder (and also possibly yields more information).

The experiment by Tamasaku *et al.* thus shows the way towards a novel spectroscopic technique to measure the optical response of chemical bonds, or valence electrons, at their natural energy and length scales. It also highlights the use of X-ray parametric down-conversion, which is the only nonlinear X-ray optical effect that has been demonstrated without use of an X-ray free-electron laser. This is a good example of an elegant, rather than extreme approach, and it can be expected that the use of subtle quantum-optical effects will be a fruitful complement to relying on the high intensity of modern X-ray sources. ❐

Bernhard Adams is at the Argonne National Laboratory, 9700 S. Cass Avenue, Lemont, Illinois 60564, USA.
e-mail: adams@aps.anl.gov

References

1. Eisenberger, P. & McCall, S. L. *Phys. Rev. Lett.* **26,** 684–688 (1971).
2. Yoda, Y., Suzuki, T., Zhang, X.-W., Hirano, K. & Kikuta, S. *J. Synchrotron Radiat.* **5,** 980–982 (1998).
3. Adams, B. W. *Nonlinear Optics, Quantum Optics, and Ultrafast Phenomena with X-Rays* (Kluwer, 2003).
4. Tamasaku, K., Sawada, K., Nishiboro, E. & Ishikawa, T. *Nature Phys.* **7,** 705–708 (2011).
5. Danino, H. & Freund, I. *Phys. Rev. Lett.* **46,** 1127–1130 (1981).
6. Freund, I. & Levine, B. F. *Phys. Rev. Lett.* **25,** 1241–1245 (1970).

Published online: 17 July 2011
Corrected online: 28 July 2011

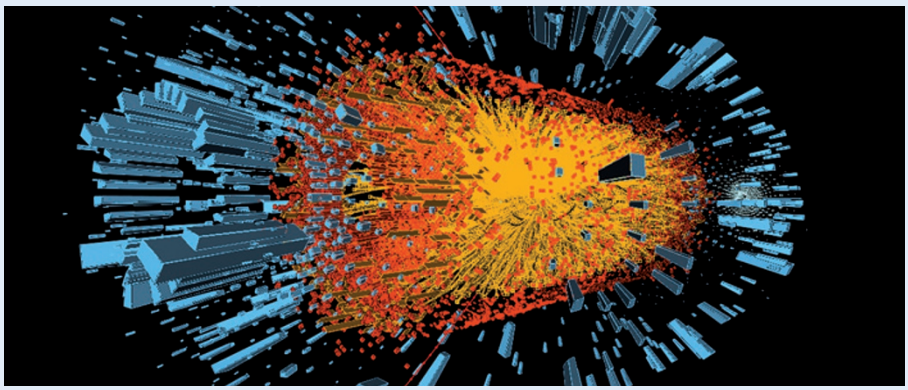
QUARK–GLUON PLASMA

In the melt

The first 'heavy-ion run' at CERN's Large Hadron Collider (LHC) took place in November last year. In place of the usual proton beams, the accelerator was primed with bunches of lead ions, brought to collision at a centre-of-mass energy of 2.76 TeV per nucleon pair. The run was primarily for the benefit of ALICE, one of the four massive detectors in the LHC ring, designed to capture the debris of these heavy-ion collisions and investigate the formation of quark–gluon plasma.

But that didn't stop two of the other detectors — ATLAS and CMS — getting in on the act. Both are general-purpose detectors that are at the forefront of LHC searches for evidence in proton–proton collisions of the Higgs boson or supersymmetry. Both succeeded in recording data during the heavy-ion run, coping with the huge particle multiplicities that are characteristic of such collisions (and illustrated here in this event from CMS).

Now, in *Physical Review Letters*, the CMS collaboration report their analysis of the production of upsilon mesons in their heavy-ion data and in a complementary set of proton–proton data taken earlier this year. The comparison reveals a suppression



CERN

of these mesons in the lead–lead collisions, which could indicate the formation of quark–gluon plasma.

At sufficiently high energy density, quarks and gluons are no longer confined but exist in a plasma, evidence of which has already emerged in earlier CERN experiments and particularly at the Relativistic Heavy Ion Collider at Brookhaven. In such an environment, bound states such as the upsilon — a bottom and antibottom quark pair — melt away. The melting temperature depends on binding energy, with excited states melting at lower temperatures than the ground state.

Upsilons decay into pairs of muons, which is a distinctive signature (the red tracks seen emerging above and below, here) that can even be picked out of heavy-ion data. Using their sample of such events, CMS have measured the ratio, for lead collisions compared with proton collisions, of another ratio — that of the production of the first two excited upsilon states to the ground state. The result is $0.31^{+0.19}_{-0.15} \pm 0.03$ (statistical and systematic errors, respectively), suggesting that upsilons are indeed melting away in the heavy-ion collisions.

ALISON WRIGHT