Based on the supersonic speed of the wave, Först and colleagues argue that the emitted shockwave is of electronic origin; this process is shown in Fig. 1. The phonons excited at the $LaAlO_3$ substrate generate electrons at the oxide interface (Fig. 1a), which then propagate at supersonic speed into the $NdNiO_3$, destroying its antiferromagnetic ordering (Fig. 1b). The general instability of the metal–insulator transition in nickelates might be directly related to the pronounced detrimental effect of the fast-travelling electrons on the magnetic and electronic properties. It cannot be fully excluded that the wave travels with the speed of sound, since its value is not really known in the strained film. This alternative scenario of a strain wave emitted from the interface that creates the metal–insulator transition without transporting the heat would be equally intriguing.

This study underlines the importance of being able to selectively excite the lattice to control electronic properties, such as the electrical resistivity of a material or its magnetic state. Being able to indirectly manipulate the electronic properties through a substrate layer offers even more interesting options for possible applications. For example, one could imagine the creation of a two-dimensional electron gas at an interface on ultrafast timescales. On the other hand, understanding the microscopic origin of the emission of electrons that occurs at the interface remains experimentally and theoretically challenging. Whether such excitations through lattice electronic waves can be created at other interfaces and are strong enough to change properties of other interesting, strongly correlated materials remains an open question. ❐

Valerio Scagnoli is at the Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland, and the Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland. Urs Staub is at the Swiss Light Source, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland.
e-mail: valerio.scagnoli@psi.ch; urs.staub@psi.ch

References

1. Yang, Z., Ko, C. Y. & Ramanathan, S. *Annu. Rev. Mater. Res.* **41,** 337–367 (2011).
2. Cavalleri, A., Dekorsy, T., Chong, H. H. W., Kieffer, J. C. & Schoenlein, R. W. *Phys. Rev. B* **70,** 161102(R) (2004).
3. Kim, H-T. *et al. Phys. Rev. Lett.* **97,** 266401 (2006).
4. Beaud, P. *et al. Nature Mater.* **13,** 923–927 (2014).
5. Huber, T. *et al. Phys. Rev. Lett.* **113,** 026401 (2014).
6. Först, M. *et al. Nature Mater.* **14,** 883–888 (2015).
7. Scagnoli, V. *et al. Phys. Rev. B* **73,** 100409(R) (2006).
8. García-Muñoz, J. L., Aranda, M. A. G., Alonso, J. A. & Martínez-Lope, M. J. *Phys. Rev. B* **79,** 134432 (2009).
9. Scherwitzl, R. *et al. Phys. Rev. Lett.* **106,** 246403 (2011).
10. Caviglia, A. D. *et al. Phys. Rev. B* **88,** 220401 (2013).

2D MATERIALS

Ultrafast exciton dynamics

Time-resolved measurements of the exciton dynamics in tungsten diselenide monolayers reveal ultrafast radiative recombination of the exciton ground state (~150 fs) and the interplay between optically bright and dark excitons.

Xavier Marie and Bernhard Urbaszek

Two-dimensional semiconductor structures based on monolayer transition metal dichalcogenides (TMDCs) such as MoS_2 and WSe_2 show very strong light–matter interaction, with absorption on the order of 10% per monolayer in the visible region of the optical spectrum. This makes these 2D materials attractive for optoelectronics applications. Their optical properties are governed by robust excitons, electron–hole pairs tightly bound by Coulomb attraction. Although indispensable for designing future devices, a clear microscopic understanding of the exciton structure and recombination is still lacking.

Rupert Huber and colleagues report in *Nature Materials* a detailed investigation of the exciton characteristics in WSe_2 monolayers[1]. Their ultrafast measurements consist of two steps: first a femtosecond pump pulse in the visible range creates the exciton in its ground state; second, an infrared probe pulse induces a transition from the exciton ground state to an excited one. These experiments provide new information on both the exciton dynamics, such as its radiative lifetime, and on the internal structure of this two-particle complex.

In TMDC monolayers reduced screening of the Coulomb interaction and ideal 2D confinement lead to gigantic exciton binding energies E_b ~500 meV, ensuring that the excitons are stable at room temperature. The onset of optical absorption is given by E_b below the free-carrier bandgap. Analogous to two-particle complexes such as the hydrogen atom, excitons in TMDC monolayers possess a centre-of-mass momentum K and an internal quantum state that accounts for the motion of the electron and the hole relative to each other, with the ground state labelled 1*s* and the first excited states being 2*s* and 2*p*. In contrast, however, to the hydrogen atom, the spacing and order of the 1*s*, 2*s*, 2*p*, and so on, levels cannot be explained with simple Rydberg series, as recently shown by one- and two-photon optical spectroscopy experiments based only on interband transitions[2].

Despite providing a wealth of information, these optical interband measurements are restricted to a small subset of excitons due to symmetry and momentum conservation: the optically active excitons that lie in the so-called radiative cone with $K \sim 0$. Huber and co-workers investigate for the first time in TMDC monolayers intra-excitonic transitions between different exciton quantum states, as initially demonstrated in bulk germanium and silicon[3,4]. In contrast to interband absorption that can be used to measure the ability to generate bound electron–hole pairs, intra-excitonic absorption experiments probe existing excitons through transitions from the 1*s* ground state to higher relative-momentum states, such as 2*p*.

In the two-colour pump–probe scheme used by Huber and colleagues, the exciton 1*s* ground state is photogenerated by a femtosecond pulsed laser and the intra-excitonic transition is then probed with a phase-locked mid-infrared pulse. The measurements reveal a clear absorption resonance for an infrared photon energy of 165 meV. With this photon energy, the 1*s* exciton can be promoted to the 2*p* orbital exciton resonance, in agreement with the 1*s*–2*p* energy spacing measured by interband excitation spectroscopy[5].

Intra-excitonic transitions $1s \rightarrow 2p$ can be induced for all values of the centre-of-mass momentum K, not only for the $K \sim 0$ excitons within the light cone (bright states)[6]. Intra-excitonic resonances can thus provide access to the entire exciton population in momentum space, including

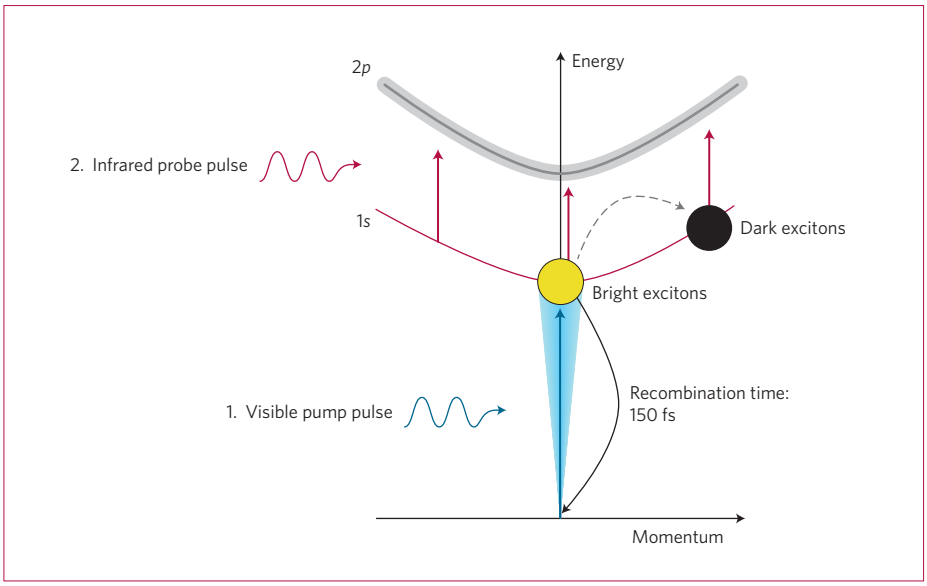

Figure 1 | Schematic of the two-colour pump–probe experiment that reveals the ultrafast exciton dynamics in a WSe_2 monolayer. A visible pump pulse populates the 1s exciton state, while the infrared probe pulse that follows, can promote bright and dark excitons — inside and outside the light cone (blue shading) — to the 2*p* states.

excitons that appear 'dark' in standard interband spectroscopy (Fig. 1).

Huber and co-workers also investigated the 1*s* exciton dynamics: as the infrared pulses that probe the generated excitons arrive after an experimentally adjustable delay, the $1s \rightarrow 2p$ transition is in competition with the 1*s* exciton recombination. Bright and dark exciton dynamics are governed by distinctly different processes: outside the light cone, non-radiative Auger recombination dominates. For excitons inside the light cone, radiative recombination with a typical decay time of 150 fs prevails[7]. This decay is considerably shorter than in other semiconductors due to the very large exciton oscillator strength in these atomically flat 2D materials. Attempts with other time-resolved techniques were not as conclusive, due to insufficient time-resolution for photoluminescence measurements[8,9] or the complexity of interpretations of many-body interactions for pump–probe experiments based on transmission or reflectivity[10]. The 150-fs recombination time measured by Huber and colleagues is shorter than the average radiative lifetime of an exciton population, resulting from the intricate interplay between bright and dark exciton populations[11], probed by standard interband spectroscopy such as photoluminescence.

Although the experiments carried out by Huber and colleagues have been performed at room temperature, similar investigations at lower temperature and possibly in the terahertz domain should allow uncovering of the complementary aspects of the exciton dynamics and fine-structure. Important for optoelectronics, these experiments should help to clarify the origin of the very low emission yield of these TMDC monolayers, which is a key obstacle for real applications as efficient emitters. In the more fundamental context of valleytronics, these two-colour pump–probe experiments will help verify exciting predictions such as the Berry curvature-induced splitting of the 2*p* exciton state[12]. ❐

Xavier Marie and Bernhard Urbaszek are at the Laboratory of Physics and Chemistry of Nano-Objects (LPCNO), UMR 5215 INSA-CNRS-UPS, 135 avenue de Rangueil, 31077 Toulouse, France.
e-mail: marie@insa-toulouse.fr; Bernhard.Urbaszek@insa-toulouse.fr

References

1. Poellmann, C. *et al. Nature Mater.* **14,** 889–893 (2015).
2. He, K. *et al. Phys. Rev. Lett.* **113,** 026803 (2014).
3. Shaklee, K. L. & Nahory, R. E. *Phys. Rev. Lett.* **24,** 942–945 (1970).
4. Ohyama, T. *Phys. Rev. B* **23,** 5545–5453 (1981).
5. Wang, G. *et al. Phys. Rev. Lett.* **114,** 97403 (2015).
6. Groeneveld, R. H. M. & Grischkowsky, D. *J. Opt. Soc. Am.* **11,** 2502–2507 (1994).
7. Wang, H. *et al.* Preprint at http://arXiv.org/abs/1409.3996 (2014).
8. Korn, T. *et al. Appl. Phys. Lett.* **99,** 102109 (2011).
9. Lagarde, D. *et al. Phys. Rev. Lett.* **112,** 047401 (2014).
10. Shi, H. *et al. ACS Nano* **7,** 1072–1080 (2013).
11. Palummo, M. *et al. Nano Lett.* **15,** 2794–2800 (2015).
12. Srivastava, A. & Imamoglu, A. Preprint at http://arXiv.org/abs/1507.04040 (2015).

CANCER TREATMENT

Low-energy electron therapy

The fabrication of a self-sustaining source of low-energy electrons in a single-atom layer could help unravel fundamental mechanisms of radiobiological damage and lead to improved cancer therapies.

Léon Sanche

In radiotherapy, high-energy photons or charged particles are directed towards cancerous tissue, destroying the malignant cells, but sparing healthy tissue as much as possible. The major products that form when such high-energy radiation interacts with a biological environment are ions and secondary low-energy (0–30 eV) electrons (LEEs)[1]. These electrons carry a large portion of the radiation energy and therefore drive many of the subsequent changes in the chemistry of the surroundings, which can cause damage to cancerous cells. Understanding their interaction mechanisms in biological media is therefore crucial for improving cancer treatments, both those that utilize radiation alone and those in combination with chemotherapy. Moreover, the destructive effects of LEEs on vital biomolecules, combined with their extremely short interaction range (~10 nm), make them ideal for targeted cancer therapies[2], in which the source of radiation is delivered directly to the cancer cells or the tumour. During the