In conclusion, Xu and colleagues' fantastic work solves a controversial issue and provides a proof of principle for similar studies in other solid tumours. Once again, retinoblastoma acts as a model for the cancer field. Knowledge of the cell of origin for retinoblastoma (and other cancers) may help researchers to develop approaches for better diagnosis, earlier detection, and possibly chemoprevention. In addition, a better understanding of the molecular circuitry that renders cells susceptible to cancerous transformation may help to uncover Achilles heels in tumour cells. ■

Rod Bremner *is at Mount Sinai Hospital, Lunenfeld Tanenbaum Research Institute, Toronto, Ontario M5G 1X5, Canada.*
Julien Sage *is in the Departments of Pediatrics and Genetics, Stanford University, Stanford, California 94305, USA.*
e-mails: bremner@lunenfeld.ca; julsage@stanford.edu

1. Xu, X. L. *et al. Nature* **514,** 385–388 (2014).
2. Friend, S. H. *et al. Nature* **323,** 643–646 (1986).
3. Visvader, J. E. *Nature* **469,** 314–322 (2011).
4. Sage, J. *Genes Dev.* **26,** 1409–1420 (2012).
5. Kyritsis, A. P., Tsokos, M., Triche, T. J. & Chader, G. J. *Nature* **307,** 471–473 (1984).
6. Rootman, D. B. *et al. Br. J. Ophthalmol.* **97,** 59–65 (2013).
7. Calo, E. *et al. Nature* **466,** 1110–1114 (2010).
8. Dyer, M. A. & Bremner, R. *Nature Rev. Cancer* **5,** 91–101 (2005).
9. Sangwan, M. *et al. Oncogene* **31,** 5019–5028 (2012).
10. McEvoy, J. *et al. Cancer Cell* **20,** 260–275 (2011).
11. Conkrite, K., Sundby, M., Mu, D., Mukai, S. & Macpherson, D. *J. Clin. Invest.* **122,** 1726–1733 (2012).
12. Xu, X. L. *et al. Cell* **137,** 1018–1031 (2009).
13. Chen, D., Chen, Y., Forrest, D. & Bremner, R. *Cell Death Differ.* **20,** 931–940 (2013).

This article was published online on 24 September 2014.

SOLID-STATE PHYSICS

A historic experiment redesigned

Large quasiparticles known as Rydberg excitons have been detected in a natural crystal of copper oxide. The result may find use in applications such as single-photon logic devices. SEE LETTER P.343

SVEN HÖFLING & ALEXEY KAVOKIN

An exciton is a quasiparticle in a solid-state system comprising an electron and a hole (the absence of an electron). It has an energy spectrum akin to that of a hydrogen atom, and so may be considered as an artificial hydrogen atom in a solid-state environment, with the hole playing the part of the hydrogen's proton. The concept of excitons was first formulated in the early 1930s by Yakov Frenkel[1], who predicted their existence in molecular crystals. A few years later, Gregory Wannier[2] and Nevill Mott[3] described these electron–hole bound states for inorganic semiconductors. In 1952, Evgeniy Gross and Nury Karryjew[4] discovered these Wannier–Mott excitons experimentally in a copper oxide (Cu_2O) semiconductor. Now, on page 343 of this issue, Kazimierczuk *et al.*[5] report how they have redesigned this historic experiment to find excitons in a natural crystal of copper oxide. The excitons extend across some tens of billions of lattice sites of the crystal.

Gross and Karryjew's discovery marked the beginning of 'excitonics' — an area of solid-state physics that holds promise for applications in optoelectronics and in information and communication technologies[6]. For their studies, Gross and Karryjew selected crystals of copper oxide, and, using a spectrograph, identified eight dark lines in the material's transmission spectrum. Such absorption dips indicated the energies of optically induced transitions from the crystal's ground state to excited states with principal quantum numbers $n = 2, 3, \dots 9$ (Fig. 1). The transition energies scaled with n in a similar way to those of a hydrogen atom. This result proved that hydrogen-like quasiparticles, excitons, can be generated in these semiconductor crystals by photoabsorption.

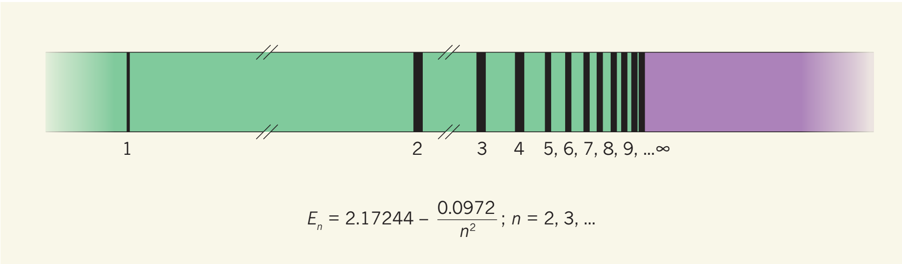
In their study, Kazimierczuk *et al.* performed high-resolution transmission spectroscopy of an extremely high-quality natural crystal of copper oxide found at the Tsumeb mine in Namibia using laser light of tunable frequency and ultralow spectral linewidth (corresponding to roughly 1.2 megahertz). Taking advantage of the narrow linewidth of the laser and the high purity of the crystal, the authors have measured transmission spectra of the material with a spectral resolution of 5 nanoelectronvolts — an extremely high value for optical spectroscopy experiments. Analysis of the spectra revealed absorption lines associated with excitons with principal quantum numbers as large as $n = 25$. The size of an exciton increases as n^2, with $n = 25$ corresponding to a

50 Years Ago

In general, the 'epidemic' process can be characterized as one of transition from one state (susceptible) to another (infective) where the transition is caused by exposure to some phenomenon (infectious material) … People are susceptible to certain ideas and resistant to others. Once an individual is infected with an idea he may in turn, after some period of time, transmit it to others. Such a process can result in an intellectual 'epidemic' … The development of the psychoanalytic movement in the early part of the twentieth century was in its way no less an 'epidemic' than was the outbreak of influenza in 1917 and 1918. One can argue similarly that Darwin and evolution, Cantor and set theory, Newton and mechanics, and so on, were examples of 'epidemics' in the world of scientific thought which were instigated by the introduction of a single infective into a population.
From *Nature* 17 October 1964

100 Years Ago

At the present time astronomers have no available organisation by which the news of important astronomical discoveries can be quickly distributed to the leading observatories of the world, nor is there a bureau with which anyone making an important discovery can immediately communicate with the knowledge that the news will at once be circulated world wide. This condition of affairs is due to the fact that the recognised Central Bureau is at Kiel, in Germany, and that the state of war prevents the circulation of any such news … There is little doubt that if the Royal Astronomical Society of Great Britain would undertake … the task of receiving and disseminating astronomical information, this act would meet with the approval of astronomers all the world over.
From *Nature* 15 October 1914



RUBEN SEISYAN/REF. 4

Figure 1 | The spectral signatures of excitons. The diagram shows the spectral absorption dips (black) associated with the hydrogen-like transitions of Wannier–Mott excitons in a copper oxide crystal. In their historic 1952 experiment[4], Gross and Karryjew identified the eight dips that correspond to transition energies E_n, with $n = 2, 3, \ldots 9$. The transition with energy E_1 is forbidden by optical-selection rules and cannot be observed. Kazimierczuk *et al.*[5] have observed excitons in a natural crystal of copper oxide with n as large as 25. The energies are given in electronvolts.

huge quasiparticle filling a sphere of diameter more than 2 μm — about ten times the wavelength of the light needed to create this exciton (see Fig. 1 of the paper[5]). Moreover, the authors found that excitons that formed at different locations in the crystal had, within the experimental accuracy of the measurements, identical spectral lines. This observation confirmed the extraordinary quality of the sample.

Such enormous quasiparticles, called Rydberg excitons, exhibit unusual quantum phenomena. One of them is giant diamagnetism, which is related to the excitons' ability to counteract an applied magnetic field. This results in a blueward shift of the excitons' spectral lines. Giant diamagnetism in copper oxide was first observed by Gross and colleagues[7], and the present experiments confirm this. Another phenomenon observed by Kazimierczuk and co-workers is Rydberg blockade, which manifests as a reduction in excitonic absorption with increasing laser power for lines that correspond to large n. Rydberg blockade means that only a limited number of large Rydberg excitons is permitted within a given volume of the crystal. The effect could be used to make nonlocal all-optical switches and single-photon logic devices.

Kazimierczuk and colleagues' discovery of giant Rydberg excitons opens up new avenues for the field of excitonics. Furthermore, the standard descriptions of light–matter interaction, in a regime in which the size of the exciton resulting from the interaction exceeds the wavelength of light used to create it, need to be revised. The long-standing assumption that extra boundary conditions for the exciton wavefunction, such as Pekar boundary conditions[8], must be included in the classical calculation of optical excitations in crystals acquires new importance in view of the nonlocal optical properties introduced in the crystals by giant Rydberg excitons: the light-induced creation of such an exciton at point A in a crystal may strongly modify the crystal's optical properties at point B if B is separated from A by more than 1 μm. Also, the fine structure of the absorption lines associated with excitons of large n may be complex and unusual owing to multiple emission and absorption of virtual photons by the excitons[9] and interactions between the spins and orbital momenta of the excitons' electrons.

Finally, with $n = 25$ having now been achieved, the question arises of whether researchers might be able to observe excitons with principal quantum numbers as large as $n = 50$, for which the exciton would have a diameter of about 1 mm — and so would, in principle, be visible to the naked eye. Answering this question would require Kazimierczuk and colleagues' experiment to be performed at millikelvin temperatures (the present experiments were done at 1.2 K), with a spectral resolution of about 1 neV. This might seem challenging, but is perhaps not impossible. ■

Sven Höfling *is in the Scottish Universities Physics Alliance, School of Physics and Astronomy, University of St Andrews, St Andrews KY16 9SS, UK.* **Alexey Kavokin** *is at the Saint Petersburg State University, St Petersburg, Russia, and at the Physics and Astronomy School, University of Southampton, Southampton SO17 1BJ, UK.*
e-mails: sh222@st-andrews.ac.uk; a.kavokin@soton.ac.uk

1. Frenkel, J. *Phys. Rev.* **37,** 1276–1294 (1931).
2. Wannier, G. H. *Phys. Rev.* **52,** 191–197 (1937).
3. Mott, N. F. *Trans. Faraday Soc.* **34,** 500–506 (1938).
4. Gross, E. F. & Karryjew, N. A. *Dokl. Akad. Nauk SSSR* **84,** 471–474 (1952).
5. Kazimierczuk, T., Fröhlich, D., Scheel, S., Stolz, H. & Bayer, M. *Nature* **514,** 343–347 (2014).
6. Baldo, M. & Stojanović, V. *Nature Photon.* **3,** 558–560 (2009).
7. Gross, E. F., Zakharchenia, B. P. & Reinov, N. M. *Dokl. Acad. Sci. USSR* **111,** 564–568 (1956).
8. Pekar, S. I. *Zh. Eksp. Teor. Fiz. USSR* **33,** 1022–1036 (1957).
9. Hopfield, J. J. *Phys. Rev.* **112,** 1555–1567 (1958).

GENOMICS

Of monarchs and migration

The genomes of 101 monarch butterflies from migratory and resident populations have been sequenced, revealing genes and molecular pathways that underlie insect migration and coloration. **SEE ARTICLE P.317**

RICHARD H. FFRENCH-CONSTANT

In 1902, Rudyard Kipling wrote the *Just So Stories*, which explained, in colourful terms, how the leopard got his spots and the camel got his hump. Half a century later, Francis Crick and James Watson discovered the molecular structure of DNA[1], but despite the molecular revolution that followed, we still struggle to explain many examples of natural selection at more than a 'just so' level. Now, owing to the application of modern DNA sequencing to systems other than mice and humans, butterflies are leading a renaissance in our understanding of the molecular basis of natural selection[2,3]. In this issue, Zhan *et al.*[4] (page 317) sequence a remarkable 101 butterfly genomes, and tell a story of two parts — migration and coloration.

During the summer, the monarch butterfly (*Danaus plexippus*) searches for milkweed plants on which to lay its eggs. Monarch caterpillars acquire cardiac glycoside compounds, which are toxic to predators, from the plant. These compounds are stored in both the caterpillars and the butterflies, which display the warning colours orange, black and white (Fig. 1). In the autumn, North American monarchs migrate and congregate in trees in the Mexican mountains. Tropical monarchs are not strictly migratory, although populations do make short-range migrations in the dry season.

Which evolved first, the temperate migratory populations or the resident tropical groups? For birds, the 'southern home' theory suggests that migratory populations arose from non-migratory tropical populations[5]. Surprisingly, Zhan and colleagues' analysis of migratory and non-migratory monarchs