



**Figure 1 | Exciton emission.** Semiconductors contain electrons and holes (absences of electrons) that can combine to form bound states called excitons. **a**, In singlet excitons, the intrinsic angular momenta (spins) of the electron and the hole point in opposite directions, which facilitates the emission of light. **b**, Conversely, in triplet states, the spins point in the same direction. Conventional wisdom holds that such states are dark, but Becker *et al.*<sup>1</sup> report that semiconductors known as lead halide perovskites emit light through bright triplet excitons.

to another form of angular momentum (namely, orbital momentum), the sum of the two momenta needs to be conserved, rather than the spin alone. The effect is known as spin–orbit coupling in atomic physics and as intersystem crossing in the study of organic semiconductors. It is responsible for weak emission from triplet states in atoms and organic molecules, especially when heavy elements are involved. However, until now, the strength of triplet emission was thought always to be inferior to that of singlet emission.

Lead halide perovskites seem to dispose of all conventional wisdom in materials science. Like organic semiconductors, they are relatively easy to fabricate, and their bandgap (a property that determines their conductivity and optical properties) can be tuned by varying their composition. Yet, like thin-layer (epitaxial) inorganic semiconductors, they are highly crystalline and exhibit efficient charge transport. It is as if their properties were selected from a materials scientist's wish list, combining the best aspects of organic molecules, nanocrystals and epitaxial inorganic semiconductors.

Becker and colleagues' study suggests that there is another feature of lead halide perovskites to be added to this list. The authors used a combination of theoretical and experimental work to show that nanocrystals of caesium lead halide perovskites ( $\text{CsPbX}_3$ , where X is chlorine, bromine or iodine) have bright triplet excitons (Fig. 1). This property results in an emission rate surpassing that of other known nanocrystals<sup>5</sup>.

The energy difference between the triplet and singlet states in  $\text{CsPbX}_3$  nanocrystals is relatively small (of the order of 1 millielectronvolt). Becker *et al.* therefore explored the material's emission at cryogenic temperatures (a few kelvin), to prevent

transitions between triplet and singlet states. It is unclear to what extent bright triplet states affect the material's emission efficiency at room temperature — when thermal energy greatly exceeds the singlet–triplet splitting energy and all states are equally populated. Nevertheless, the authors' findings are of fundamental relevance.

Future work will certainly investigate whether bright triplet states exist in other types of perovskite, such as hybrid perovskites that have organic, positively charged ions (cations). Such materials include the archetypal methylammonium lead iodide ( $\text{CH}_3\text{NH}_3\text{PbI}_3$ ), and are typically prepared not as nanocrystals,

**“The authors’ study highlights the potential of perovskite materials as efficient light emitters.”**

but as solid-state films<sup>6</sup>. Unlike  $\text{CsPbX}_3$  nanocrystals, these films comprise micrometre- or millimetre-sized crystalline domains, in which excitons dissociate into pairs of free electrons and holes at room temperature. More generally, Becker and colleagues' theoretical analysis might help scientists to identify other semiconducting materials (either organic or inorganic) that have bright triplet excitons.

Research into hybrid perovskites has been fuelled in the past few years by the successful incorporation of these materials into solar cells. Such devices can now convert more than 22% of the energy received from sunlight into electricity<sup>7</sup>, which is a record for perovskite solar cells. However, because of a concept known as quantum-mechanical reciprocity, there is an unavoidable energy loss in solar cells: that due to photoluminescence, which is the reverse of the absorption process<sup>8</sup>. As a consequence, the best solar cells are also the

best light emitters — an idea reinforced by Becker and colleagues' work.

Perovskite solar cells are now leaving academic labs and entering the market, thanks to substantial industrial efforts. The competition is mainly silicon solar cells, which have become so cheap that they negate some of the advantages of perovskite fabrication. For this reason, tandem solar cells (consisting of two sub-cells) and innovative architectures involving perovskites are being developed that can outperform commercial silicon devices in terms of efficiency, if not cost<sup>9</sup>.

Light emission is an application in which organic semiconductors and nanocrystals have already found commercial success, because of their ability to produce vivid colours and to be incorporated into thin panels. And yet the electric-current densities in organic light-emitting diodes are much lower than in their inorganic counterparts as a result of poor electrical conductivity. Perovskites could allow high current densities and efficiencies to be realized on large-area, thin panels<sup>10</sup>.

Becker and colleagues' study highlights the potential of perovskite materials as efficient light emitters. Although the findings might seem surprising at first sight, they should be seen as a natural consequence of quantum-mechanical reciprocity — that the class of material brought to the forefront by solar-cell technology could find applications in light emission. ■

Michele Saba is in the Department of Physics, University of Cagliari, I-09042 Monserrato, Italy.

e-mail: saba@unica.it

1. Becker, M. A. *et al. Nature* **553**, 189–193 (2018).
2. Pope, M. & Swenberg, C. E. *Electronic Processes in Organic Crystals* (Oxford Univ. Press, 1999).
3. Reineke, S., Thomschke, M., Lüssem, B. & Leo, K. *Rev. Mod. Phys.* **85**, 1245–1293 (2013).
4. Demtröder, W. *Atoms, Molecules and Photons* (Springer, 2010).
5. Rainò, G. *et al. ACS Nano* **10**, 2485–2490 (2016).
6. Stoumpos, C. C. & Kanatzidis, M. G. *Acc. Chem. Res.* **48**, 2791–2802 (2015).
7. Correa-Baena, J.-P. *et al. Science* **358**, 739–744 (2017).
8. Rau, U. *Phys. Rev. B* **76**, 085303 (2007).
9. Eperon, G. E., Hörantner, M. T. & Snaith, H. J. *Nature Rev. Chem.* **1**, 0095 (2017).
10. Colella, S., Mazzeo, M., Rizzo, A., Gigli, G. & Listorti, A. *J. Phys. Chem. Lett.* **7**, 4322–4334 (2016).

#### CORRECTION

The News & Views article ‘Cancer: Tumour lymph vessels boost immunotherapy’ by Christine Moussion and Shannon J. Turley (*Nature* **552**, 340–342; 2017) cited reference 2 incorrectly. The correct reference is: S. L. Topalian, C. G. Drake & D. M. Pardoll *Cancer Cell* **27**, 450–461 (2015).