could be the first step in the formation of large carbon-containing molecules in general: subsequent (or simultaneous) exposure of the graphene to atomic hydrogen produces PAHs, whereas ion bombardment produces fullerene. Alternatively, PAH molecules might be molecular intermediates in the formation of carbon soot, which can then be broken down by ultraviolet irradiation to make PAHs again[14].

The efficiency of Bernal and colleagues' fullerene-forming mechanism is unknown, raising the question of how many SiC grains are needed to account for the observed abundance of fullerene molecules in space. If there aren't enough grains, then a further mechanism will be required to explain the abundance of fullerene. By contrast, if there are too many SiC grains, what happens to the 'excess' fullerene molecules produced, given that they are notoriously difficult to degrade? More experiments and detailed modelling of the formation of fullerene and of other carbon-containing large molecules from SiC grains are needed to understand this process, and to quantify its importance in old stars.

The launch of the James Webb Space Telescope in 2021 will provide powerful new tools for studying old stars, among other astronomical objects. Observations of fullerene-containing sources[7,8] such as Tc 1 will be able to constrain the regions in which SiC grains, fullerene and PAHs are present, providing more clues about how large molecules are actually formed. Further analysis and modelling of the routes involved will eventually allow astronomers to suggest the identities of the other mysterious molecules responsible for the diffuse interstellar bands.

Alessandra Candian is at the van't Hoff Institute for Molecular Sciences, University of Amsterdam, 1090 GD Amsterdam, the Netherlands, and at the Leiden Observatory, University of Leiden, Leiden, the Netherlands.
e-mail: a.candian@uva.nl

1. Campbell, E. K., Holz, M., Gerlich, D. & Maier, J. P. *Nature* **523**, 322–323 (2015).
2. Jäger, C., Huisken, F., Mutschke, H., Llamas Jansa, I. & Henning, T. *Astrophys. J.* **696**, 706–712 (2009).
3. Bernal, J. J. *et al. Astrophys. J.* **883**, L43 (2019).
4. Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F. & Smalley, R. E. *Nature* **318**, 162–163 (1985).
5. Berné, O. & Tielens, A. G. G. M. *Proc. Natl Acad. Sci. USA* **109**, 401–406 (2012).
6. Zhen, J., Castellanos, P., Paardekooper, D. M., Linnartz, H. & Tielens, A. G. G. M. *Astrophys. J.* **797**, L30 (2014).
7. Cami, J., Bernard-Salas, J., Peeters, E. & Male, S. E. *Science* **329**, 1180–1182 (2010).
8. Cami, J., Peeters, E., Bernard-Salas, J., Doppmann, G. & De Buizer, J. *Galaxies* **6**, 101 (2018).
9. Frenklach, M., Carmer, C. S. & Feigelson, E. D. *Nature* **339**, 196–198 (1989).
10. Daulton, T. L. *et al. Science* **296**, 1852–1855 (2002).
11. Mishra, N., Boeckl, J., Motta, N. & Iacopi, F. *Phys. Status Solidi A* **213**, 2277–2289 (2016).
12. Croat, K. T., Bernatowicz, T. J. & Daulton, T. L. *Elements* **10**, 441–446 (2014).
13. Merino, P. *et al. Nature Commun.* **5**, 3054 (2014).
14. Cherchneff, I., Barker, J. R. & Tielens, A. G. G. M. *Astrophys. J.* **401**, 269–287 (1992).

Optical physics

Light trapping gets a boost

Kirill Koshelev & Yuri Kivshar

The ability of structures called optical resonators to trap light is often limited by scattering of light off fabrication defects. A physical mechanism that suppresses this scattering has been reported that could lead to improved optical devices. **See p.501**

Devices called optical resonators confine light, but for only a limited time because of unavoidable light emission. On page 501, Jin *et al.*[1] report that such emission can be greatly reduced by using the interference of light waves known as bound states in the continuum. Such waves are akin to exotic electron waves that were introduced in the theory of quantum mechanics almost a century ago[2]. The authors' finding could have many technological implications for nanophotonics, quantum optics and nonlinear optics – the study of how intense light interacts with matter.

Interference is a common wave phenomenon in physics, whereby two or more waves pass through one another to produce a combined waveform. Consider the case in which these waves are correlated with one another, either because they come from the same source or because they have almost the same frequency. If the crest of one wave coincides with the crest of another wave, the combined amplitude will be the sum of the individual amplitudes. And if the crest of one wave meets the trough of another wave, the combined amplitude will be the difference in the individual amplitudes. These two scenarios are called constructive and destructive interference, respectively.

The effects of interference can be observed for all waves, but interference associated with bound states in the continuum (BICs) has attracted much attention in photonics over the past few years[3]. BICs are formed by the destructive interference of several ordinary light waves that have a similar wavevector – a quantity that describes a wave's velocity and direction of propagation. This interference provides a means of achieving strong confinement of light and of increasing its amplitude through a phenomenon known as optical resonance. It can also be used to tune an optical resonator into the 'supercavity' regime, in which emission of light from the resonator is restrained[4]. Several approaches to realizing BICs have been suggested for waves in electronic, electromagnetic and acoustic systems.

The concept of BICs was proposed for unusual states of electron waves by two pioneers of quantum mechanics, John von Neumann and Eugene Wigner[2]. They discovered that specific potentials (potential-energy profiles) could support spatially localized electron states that have energies larger than the maximum energy of the potential. In other words, the states could be confined even though their energies would normally allow them to escape. In photonics, a light wave that is trapped by an optical resonator can be converted to a BIC under certain conditions[3] – a discovery that was made only in 2008.

The main characteristic of an optical resonator is the quality factor – the ratio of the time over which the device can trap light to the period of the wave's oscillation. If the light waves destructively interfere to form BICs, the quality factor greatly increases. Moreover, in the BIC regime, the quality factor theoretically tends to infinity when one of the system parameters, such as the size of the resonator, is tuned. By contrast, the quality factor of a

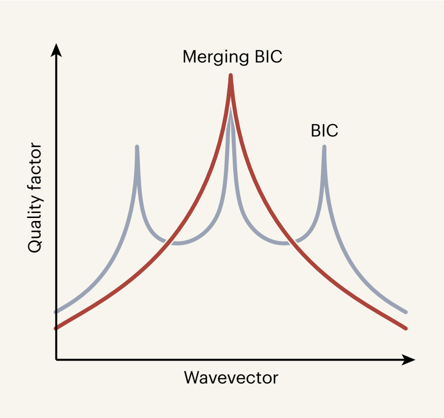

Figure 1 | Increasing the quality factor of an optical resonator. Jin *et al.*[1] report simulations of and experiments on a light-trapping device known as an optical resonator. The key characteristic of a resonator is the quality factor – a measure of the efficiency of light trapping. This quantity varies with the wavevector, which describes the velocity and propagation direction of a wave. The authors used their resonator to trap light in the form of waves called bound states in the continuum (BICs). They then combined these BICs into a single state: a merging BIC. As this graph shows, a merging BIC increases the quality factors of all waves that have similar wavevectors to it.

conventional resonance is not substantially affected by parameter variations.

In practical optical resonators, the quality factors of BICs are fundamentally limited by inevitable fabrication defects, which scatter light out of the plane of the device. Any light wave that is scattered off a structural imperfection changes its wavevector. To prevent scattering losses, waves must remain trapped in the resonator even after these changes have occurred. In other words, the quality factor needs to be high both before and after scattering.

Jin and colleagues have suggested and demonstrated an innovative physical mechanism for achieving optical resonances that are extremely robust to out-of-plane scattering. They considered a structure called a photonic crystal slab, consisting of a submicrometre-thick dielectric (electrically insulating) membrane patterned with a square lattice of circular holes.

The authors first ran numerical simulations to study the optical resonances in their membrane. By carefully selecting the membrane's parameters, they achieved several simulated BICs that had different wavevectors. They then altered the periodicity of the lattice until the BICs had the same wavevector. This gave rise to a new type of optical resonance: a merging BIC (which one might refer to as a super-BIC; Fig. 1). The hallmark of a merging BIC is that it increases the quality factor of all waves that have nearly the same wavevector as the resonance, reducing scattering losses from the resonator.

Jin *et al.* then experimentally demonstrated their mechanism by fabricating a set of silicon membranes that had different lattice periodicities. Some of these membranes supported a merging BIC at telecommunication wavelengths (about 1,550 nanometres) and others were close to this merging-BIC regime. The authors used a tunable telecommunication-wavelength laser to measure the intensity of scattered light along different directions for each of the samples. They found that the membranes supporting a merging BIC had a quality factor that was about 10 times larger than that for the membranes not in the merging-BIC regime. Moreover, they showed that the observed increase in quality factor was robust by finding a similar level of enhancement in all of the fabricated samples that had a merging-BIC design.

The demonstration could have many consequences for engineering high-quality resonances in nanophotonics. The ability to convert light waves into BICs allows the realization of the supercavity regime, in which highly compact resonators can have extremely large quality factors[5]. Dielectric materials that have high refractive indices could be used to reduce the resonator dimensions and to combine individual BIC resonators that have high-quality resonances into structured arrays[6].

We predict that an electromagnetic theory will be developed for describing high-quality resonances in individual dielectric nanoparticles of high refractive index and arrays of such nanoparticles, and that they all will be expressed in terms of the mathematics used to study interference in quantum mechanics. In the real world, the engineering of quality factors in the BIC regime could lead to substantial enhancement of nonlinear and quantum effects, the development of lasers that consume little power, and the realization of nanoscale resonators that facilitate strong confinement of light and large boosts to its amplitude.

Kirill Koshelev and **Yuri Kivshar** are at the Nonlinear Physics Centre, Australian National University, Canberra, ACT 2601, Australia, and in the Department of Nanophotonics and Metamaterials, ITMO University, St Petersburg, Russia.
e-mails: kirill.koshelev@anu.edu.au; ysk@physics.anu.edu.au

1. Jin, J. *et al. Nature* **574**, 501–504 (2019).
2. von Neumann, J. & Wigner, E. P. *Phys. Z.* **30**, 465–467 (1929).
3. Hsu, C. W., Zhen, B., Stone, A. D., Joannopoulos, J. D. & Soljačić, M. *Nature Rev. Mater.* **1**, 16048 (2016).
4. Rybin, M. & Kivshar, Y. *Nature* **541**, 165–166 (2017).
5. Rybin, M. *et al. Phys. Rev. Lett.* **119**, 243901 (2017).
6. Koshelev, K., Lepeshov, S., Liu, M., Bogdanov, A. & Kivshar, Y. *Phys. Rev. Lett.* **121**, 193903 (2018).

Epigenetics

Lactate links metabolism to genes

Luke T. Izzo & Kathryn E. Wellen

Cells regulate gene expression in part through the chemical labelling of histone proteins. Discovery of a label derived from lactate molecules reveals a way in which cells link gene expression to nutrient metabolism. **See p.575**

Cellular metabolism involves the uptake, release and biochemical interconversion of nutrients to produce energy and synthesize complex molecules. The intermediates and end products of metabolism also have essential signalling functions, modulating cell signalling and gene expression in accordance with nutritional resources[1,2]. One way in which these metabolites signal is through the chemical modification of proteins such as histones. On page 575, Zhang and colleagues[3] describe their discovery of a previously unknown histone modification, lactylation, derived from the cellular metabolite lactate.

Histones are central components of chromatin — a complex of DNA and proteins that organizes and regulates the genome. They can be altered by cellular enzymes, which add chemical tags such as methyl, acetyl and phosphate groups; these epigenetic modifications to the genome affect processes such as gene expression and DNA replication and repair. Zhang *et al.* predicted that histones might also be altered by the addition of lactyl groups, and they began their search for lactylation by using a technique called mass spectrometry, which has enabled the identification of numerous protein modifications in the past few years[4]. By looking for shifts in the masses of amino-acid residues that make up histone tails, the authors deduced the presence of a modified lysine amino-acid residue, consistent with the addition of a lactyl group. Zhang *et al.* validated this finding by comparing synthetic peptides that had been chemically modified in this way with the corresponding peptides identified in cells.

The authors also used metabolic tracing with a form of lactate labelled with a stable isotope of carbon ($^{13}C_3$-lactate) to demonstrate that lactate is involved in histone lactylation. They further found that levels of lysine lactylation rose when cells were treated with increasing doses of lactate. So, histone lactylation is derived from lactate and is sensitive to lactate levels.

Lactate is an abundant metabolite produced during glycolysis — a central metabolic process in which glucose consumed by cells is broken down to generate energy. During glycolysis, glucose is converted into two pyruvate molecules; these can be either funnelled into lactate production or transported into the cellular power generators (the mitochondria), forming the intermediate acetyl coenzyme A (acetyl-CoA) and thence entering the Krebs cycle for energy production. Lactate is produced through glycolysis in various cell types, including cancer cells and immune cells. Its production is also enhanced under certain conditions, such as hypoxia (low oxygen levels), which suppresses pyruvate entry into the Krebs cycle. Zhang and colleagues' discovery that lactate is used for histone modification is intriguing both because of the metabolite's abundance and because its production, uptake and use are all subject to dynamic regulation[5].

One substantial question that the authors