OPTICAL PHYSICS

Colour from colourless droplets

Iridescent colours have been observed to be reflected from specially designed droplets of colourless liquids, with the reflected colour depending on the viewing angle. The finding reveals a curious mechanism for creating coloration. SEE LETTER P.523

KENNETH CHAU

Humans have been searching for better ways of making colours for centuries, frequently turning to nature for inspiration. The earliest colours used in art and clothing were naturally occurring pigments and dyes, which selectively absorb certain wavelengths of visible light. By contrast, the complex colours found in butterfly wings and mother-of-pearl are produced not only from pigmentation, but also by the scattering of light from microscopic structures whose sizes are roughly the same as the wavelengths of visible light — an effect known as structural coloration. In this issue, Goodling *et al.*[1] (page 523) describe another method for achieving brilliant colours that is based on the scattering of light from small droplets. This phenomenon parallels some of the most beautiful displays of colour found in the sky.

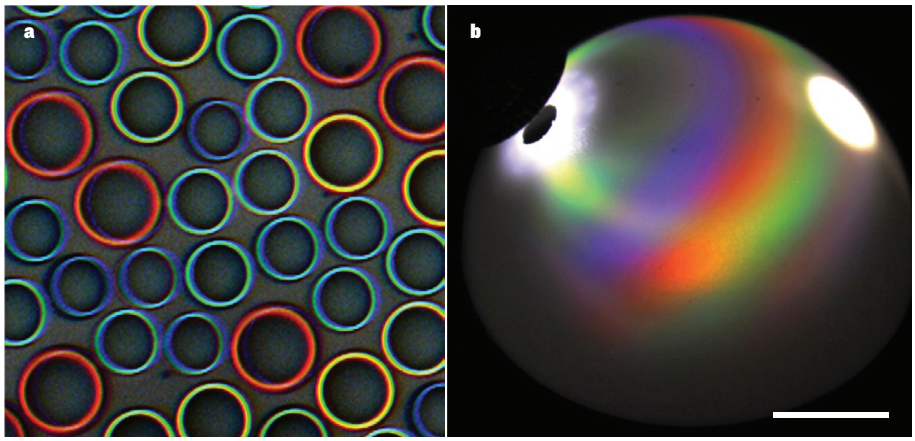

Figure 1 | Iridescent reflected light. **a**, Goodling *et al.*[1] report that asymmetrical, micrometre-scale liquid droplets dispersed in a transparent fluid medium reflect coloured light from their edges when illuminated by a beam of white light. The coloration depends on the size and shape of the droplets. **b**, The colour of the reflected light also depends on the angle at which the droplets are viewed. Here, light reflected from droplets in a Petri dish is projected onto a translucent dome placed over the dish, revealing the colours produced at different viewing angles. Scale bar, 1 centimetre.

Goodling and colleagues observed that asymmetrical, micrometre-scale liquid droplets showed pronounced coloration when a beam of white light was reflected from them. This was surprising because the droplets were inherently colourless. The coloration must therefore arise from interactions of the light with the structure of the droplets.

When the authors examined the droplets under a microscope, they observed that the coloured light emerged specifically from the edges of the droplets, and therefore forms circular haloes around the edges (Fig. 1). Moreover, the droplets were iridescent: they changed colour depending on the viewing angle, in some cases from pink to yellow, to green to blue, to no colour at all. For a fixed viewing angle, the colour of the light reflected from the droplets depended strongly on the droplet size and morphology. For example, suspensions of droplets of different sizes were a shimmering white, whereas suspensions of droplets of a similar size were a uniform colour.

Goodling *et al.* carried out a series of experiments and modelling studies to investigate the physical mechanism behind the coloration effect. Unlike the rainbow of colours obtained when white light refracts through glass, the dependence on viewing angle and the range of colours observed from the droplets cannot be explained by material dispersion (the variation of a material's refractive index as a function of wavelength).

Instead, the authors propose that light rays entering a droplet along an edge are redirected along the curved surface of the droplet by a process known as total internal reflection. The light rays pass along the droplet's interior surface and exit from the opposite edge of the droplet, acquiring a distinct colour that is due to interference between emerging light rays — the interference accentuates or mutes different wavelengths in the visible light spectrum. The acquired colour also depends on the specific path taken by light rays through the droplet, which explains why the coloration is highly sensitive to droplet size, morphology and viewing angle. Further refinement of the modelling methods, perhaps involving 3D simulations of the electromagnetic fields of the white light in the droplet, will undoubtedly uncover more details of the physics underlying this colourful effect.

Goodling and co-workers are not the first to observe colours due to light scattering from tiny droplets. Atmospheric optical effects, such as rainbows, coronas and glories, owe their brilliant displays of colour to the intricate interplay between sunlight and submillimetre-scale water droplets[2,3]. The phenomenon of glories, in particular, bears some similarity to the coloration effects observed by the authors.

Glories are most commonly seen when clouds are viewed from above (for example, from an aeroplane), and occur as concentric rings of colour around the shadow of the observer (or, if the observer is in the plane, around the plane's shadow). They are caused by the interference of rays of sunlight that have been scattered by droplets in clouds[4,5], and can be explained by a well-established set of solutions to Maxwell's equations known as Mie theory[3]. However, Mie theory describes scattering only from spherical particles, and therefore cannot be directly used to explain Goodling and colleagues' observations, which involve non-spherical particles. Further exploration is needed to determine whether the coloration of the authors' droplets shares the same physical origin as atmospheric glories.

Goodling *et al.* report that their droplets can be used in 2D arrays to create pixelated images. They manipulate the colour of each pixel by tailoring the droplet shape and size, or liquid composition. Furthermore, the coloration effect can be achieved using a wide range of materials and geometric shapes — besides droplets composed of different liquids, Goodling *et al.* demonstrate that solid particles and polymeric microstructures can also exhibit this effect.

The incorporation of this technology into

displays and sensors is an exciting prospect, but will be challenging to achieve. Unlike pigments, colours produced using this method are seen only in reflected light at certain viewing angles, and require lighting from a fixed direction, which might limit the range of possible applications. The extent to which the coloration effect can be used to manipulate and tailor the spectral signatures of reflected light remains unknown. However, this question can easily be explored, for example by incorporating pigments into the droplets to absorb specific wavelengths of light.

Another question is whether the full range of visible colours can be produced through systematic tuning of droplet shape and composition. This remains to be seen, but the range of colours achieved is already impressive, and the reported spectra are quite complex. It therefore seems possible that we could soon be able to fabricate surface structures that produce designed, iridescent patterns of light that are highly responsive to the environment and to the observer's location. ■

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1. Goodling, A. E. *et al. Nature* **566**, 523–527 (2019).
2. Bohren, C. & Huffman, D. *Absorption and Scattering of Light by Small Particles* (Wiley, 1983).
3. van de Hulst, H. C. *Light Scattering by Small Particles* (Dover, 1981).
4. Nussenzveig, H. M. *Sci. Am.* **306**, 68–73 (2012).
5. Laven, P. *Appl. Optics* **44**, 5675–5683 (2005).

MEDICAL RESEARCH

Sticking together helps cancer to spread

When cancer spreads, this metastatic stage of the disease is usually lethal. An analysis of immune cells that cluster with tumour cells in the bloodstream illuminates a partnership that might aid metastasis. SEE LETTER P.553

MIKALA EGEBLAD & KARIN E. DE VISSER

The process that determines whether cancer spreads from the original tumour site to reach distant organs is poorly understood, despite the devastating consequences for disease prognosis if this spreading step, termed metastasis, occurs. For cancer to invade other tissues and form metastases, tumour cells must travel through the body, including the bloodstream. Therefore, it can be an ominous sign if even low numbers of cancer cells, termed circulating tumour cells (CTCs), are found in blood samples[1]. If we can understand how CTCs survive in this environment, which is hostile partly because of forces (termed shear stress) encountered in blood vessels, this might enable the development of therapies to prevent metastasis. On page 553, Szczerba *et al.*[2] describe a previously unknown mechanism that enables CTCs to successfully colonize new sites in other tissues, and propose a possible vulnerability of CTCs that might offer a target for clinical treatments.

CTCs can associate with immune cells called white blood cells[3]. Szczerba *et al* studied blood samples from 70 people with an advanced stage of breast cancer and observed this type of association for an average of 3.4% of the CTCs in 34 of the patients. The authors investigated CTCs in five mouse models of breast cancer, and also found evidence that 0.05–61% of the CTCs in these models clustered with white blood cells. The authors report that the white blood cells mainly belonged to the most abundant immune-cell type in the blood, called neutrophils (Fig. 1).

Neutrophils have a crucial role in front-line defences against infectious agents. There is mounting evidence that these cells are key players in metastasis[4–8], but whether they have an effect on CTCs was unknown. Three observations led the authors to conclude that neutrophils clustering with CTCs can enhance the CTCs' metastatic potential. First, they found that the presence of CTC–neutrophil clusters in people with advanced breast cancer correlated with a shorter time until the disease advanced compared with the time until the disease advanced in people lacking these clusters. Second, when CTCs from CTC–neutrophil clusters were isolated from mice, separated from the neutrophils and injected into the bloodstream of tumour-free mice, they led to a considerably higher number of metastases than occurred in mice that received CTCs that had not been part of clusters with neutrophils. Third, if neutrophils were depleted in mice bearing breast tumours, this reduced the number of CTC–neutrophil clusters and delayed the formation of metastases in the lung compared with the situation in mice in which neutrophils were not depleted.

Why do neutrophil-associated CTCs metastasize more readily than CTCs that don't form this cellular partnership? To address this question, the authors characterized CTCs associated with neutrophils, and found that these cells had both a higher level of expression of

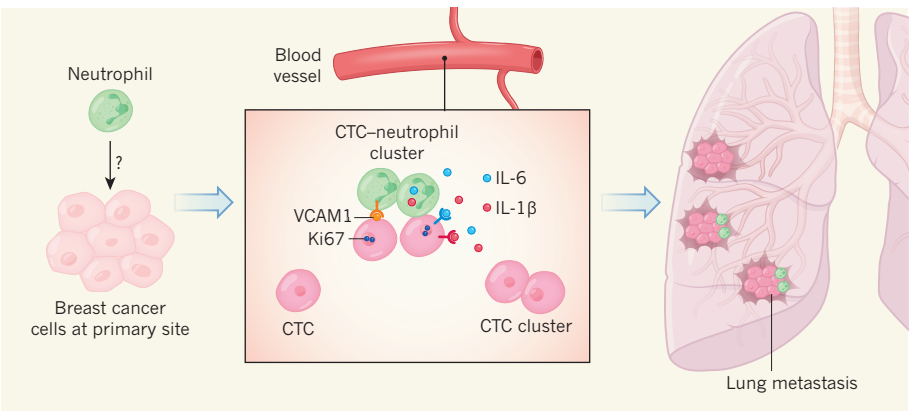

Figure 1 | Interactions between breast cancer cells and neutrophils promote the formation of lung metastases. When breast cancer cells spread from their primary site (a process termed metastasis), this is associated with poor prognosis. Szczerba *et al.*[2] report studies on clinical samples and mouse models which reveal that immune cells called neutrophils can boost the metastatic potential of tumour cells. It is not known whether neutrophils first interact with cancer cells in the primary tumour site in breast tissue. Metastatic breast cancer cells that have entered the bloodstream are called circulating tumour cells (CTCs), and they can exist individually or in clusters. The authors reveal that certain CTC clusters can also contain neutrophils. The protein VCAM1 on the tumour-cell surface is essential for the formation of these clusters, presumably because it binds to its corresponding receptor on neutrophils. Mutations in the gene *TLE1* (not shown) also promote the formation of CTC–neutrophil clusters, although the underlying mechanisms are unknown. Neutrophils clustered with CTCs express inflammatory signalling molecules, including the proteins IL-6 and IL-1β, and CTCs have the corresponding receptors for these proteins. Interactions between CTCs and neutrophils boost CTC cell-cycle progression, as indicated by the presence of a cell-cycle marker protein in the nucleus, called Ki67. The authors report that CTCs that have been associated with neutrophils are more likely to form metastases in the lung than are CTCs that have not. Whether the neutrophils remain associated with the cancer cells until they form such a metastasis is unknown.