live-coral planting have not been quantified, but Perry *et al.* provide convincing evidence that the time has come to make reef restoration a priority. A recent analysis[10] indicates that ecological restoration projects aimed at protecting shorelines might be more cost-effective than conventional projects that use engineered concrete structures. Although it is uncertain how much time we can buy for coral reefs through restoration, such projects might extend the existence of the reefs long enough to bridge the gap until global efforts start to decrease the concentration of atmospheric greenhouse gases, thereby slowing the rates of global warming and sea-level rise. ■

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1. Costanza, R. *et al. Nature* **387**, 253–260 (1997).
2. Perry, C. T. *et al. Nature* **558**, 396–400 (2018).
3. Hughes, T. P. *et al. Nature* **546**, 82–90 (2017).
4. Perry, C. T. *et al. Coral Reefs* **31**, 853–868 (2012).
5. Church, J. A. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. *et al.*) Ch. 13 (Cambridge Univ. Press, 2013).
6. Hubbard, D. K., Miller, A. I. & Scaturo, D. *J. Sedimentol. Petrol.* **60**, 335–360 (1990).
7. Tribollet, A., Godinot, C., Atkinson, A. & Langdon, C. *Global Biogeochem. Cycles* **23**, GB3008 (2009).
8. Silbiger, N. J. & Donahue, M. J. *Biogeosciences* **12**, 567–578 (2015).
9. Webster, P. J., Holland, G. J., Curry, J. A. & Change, H.-R. *Science* **309**, 1844–1846 (2005).
10. Morris, R. L., Konlechner, T. M., Ghisalberti, M. & Swearer, S. E. *Glob. Change Biol.* **24**, 1827–1842 (2018).

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NANOSCIENCE

# Frictionless when flat

**Gas transport in nanoscale channels that have perfectly flat walls has been found to be frictionless, challenging the classical theory of gas flow. The findings might enable new devices for gas separation and flow control.** **SEE LETTER P.420**

CHUANHUA DUAN

In classical physics, frictionless gas flow through channels is a phenomenon that can occur only under ideal conditions. A key requirement is that the gas molecules undergo specular reflection from the channel walls — they rebound so that their angle of incidence is the same as the angle of reflection. In reality, gas molecules are thought to rebound from walls in all directions, a behaviour known as diffuse reflection. But can diffuse reflection be switched to specular reflection to achieve frictionless gas transport, and, if so, what are the fundamental requirements for this? On page 420, Keerthi *et al.*[1] answer these questions by investigating gas transport through two-dimensional, nanometre-scale channels that have atomically flat walls.

Achieving specular reflection for gas molecules seems an impossible task. Even the best, artificially polished surface is randomly bumpy at the tiny scales associated with gas molecules (which are about $10^{-9}$–$10^{-10}$ metres in diameter). It is this bumpiness that is thought to make gas molecules rebound in all directions, causing diffuse reflection. The concept of diffuse reflection underpins Knudsen theory, which has generally provided a good description of gas transport through channels. But what happens if the channel surfaces are genuinely flat?

To answer this question, Keerthi *et al.* prepared nanochannels[2,3] from materials that consist of stacked, 2D layers of atoms: graphite, hexagonal boron nitride (h-BN) and molybdenum disulfide ($MoS_2$). These materials can be cleaved to form 2D crystals that are as thin as a single layer of atoms, and have atomically flat surfaces. 2D crystals made from different materials can easily stack together, because strong van der Waals forces form between their flat surfaces[4]. The authors made their nanochannels by sandwiching a 2D crystal containing a narrow gap between two other 2D crystals (Fig. 1). The channels are well sealed, and their heights can be precisely controlled by the number of layers of atoms in the middle 2D crystal.

The researchers measured the flow of gas through the nanochannels under low pressure. Under these conditions, the gas molecules collide mostly with the surfaces of the channels, rather than with each other. The authors found that the permeability of helium through nanochannels made from graphite or h-BN, whose surfaces are flat even at scales of 1 ångström ($10^{-10}$ m), is ten to several hundred times higher than predicted by Knudsen theory. Furthermore, they observed that the highest helium permeability measured in graphite nanochannels was independent of the channel length, indicating that there is no momentum loss in the channels and that frictionless flow has been achieved.

By contrast, the permeability of helium through $MoS_2$ nanochannels was the same as that predicted by Knudsen theory. This is

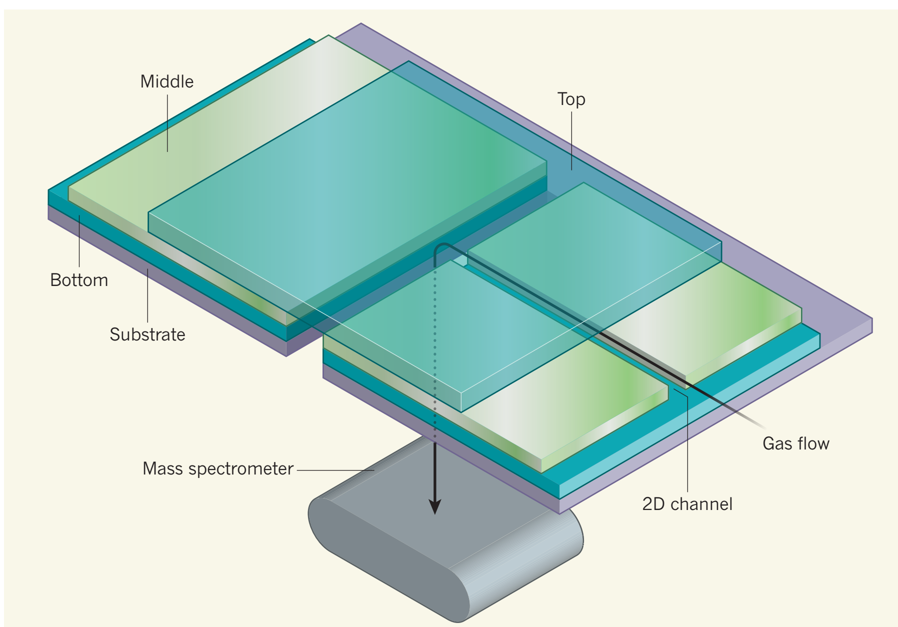


**Figure 1 | Measuring gas flow though 2D channels.** Keerthi *et al.*[1] prepared nanochannels from materials that can be cleaved to produce 2D crystals just one or a few layers of atoms thick. The nanochannels were made by sandwiching a 2D crystal (middle layer) containing a narrow gap between two other 2D crystals (top and bottom layers). The authors then measured the flow of gas — helium, hydrogen or deuterium — through the channels using a mass spectrometer. In channels made of graphite and hexagonal boron nitride, they observed much higher gas flow than is predicted by classical theory; this flow was confirmed to be frictionless in the graphite channels. However, gas flow conforming to classical theory was observed in channels made of molybdenum disulfide. The properties of the flow seem to depend on the roughness of the channel surfaces as 'perceived' by the gas molecules.

because $MoS_2$ is rougher at atomic scales than is graphite (and h-BN). Through computational modelling, the authors found that $MoS_2$ surfaces have bumps around 1 Å in height, which is comparable to the diameter and the de Broglie wavelength of helium molecules (all matter can exhibit wave-like behaviour, and the de Broglie wavelength is the wavelength associated with that behaviour). In other words, the $MoS_2$ nanochannels are too bumpy for specular reflection.

Keerthi and colleagues' findings prove that complete specular reflection and frictionless gas transport can occur in nanochannels that have perfectly flat surfaces. This is an exciting discovery, because previous studies[5,6] have reported only partial specular reflection. Even more intriguingly, the authors make several unexpected observations, some of which cannot be explained by classical physics.

The first and most important of these observations is that frictionless gas transport is affected by the matter waves of the gas molecules. The authors found that the permeability of deuterium ($D_2$) in graphite nanochannels is much lower than that of hydrogen ($H_2$), its lighter isotopic counterpart, even though Knudsen theory predicts the opposite. This is because deuterium molecules have a smaller de Broglie wavelength than do hydrogen molecules, and therefore 'see' the channel walls as being rougher, even though the two types of molecule have the same diameter and interact in the same way with the channel walls. The authors also showed that computational simulations of gases that represent classical molecule–wall interactions, but not quantum effects (that is, the effects of matter waves), predict only partial, rather than complete, specular reflection in graphite and h-BN nanochannels. This suggests that quantum effects must contribute to specular reflection.

The other interesting observation is that the permeability of helium in graphite and h-BN channels varies unexpectedly with channel height: it initially increases, then decreases as the channel height increases, reaching a maximum value for heights of four atom layers. This behaviour is at odds with conventional thinking that complete specular reflection is not affected by channel height. Keerthi *et al.* speculate that the height dependence results from the interplay between two effects: small channels have relatively small 'capture zones' for incident gas molecules at their entrances, whereas hydrocarbons from the surrounding air can be adsorbed to larger channels during channel fabrication, roughening the atomically flat surface. Neither of these effects is included in existing models of gas flow, but they seem to have key roles in determining permeability in the real world.

The new findings call for a re-examination of the classical physics of gas dynamics at low pressure and its correlation with quantum mechanics. However, more experiments with other gases in graphite and h-BN nanochannels are needed to further unravel the influence of molecular diameter and de Broglie wavelength on specular reflection, given that larger diameters typically correspond to smaller de Broglie wavelengths. Moreover, a quantitative comparison of gas transport through rectangular nanochannels and through circular nanotubes made of the same material is needed to evaluate the effect of channel curvature.

In addition, the factors that cause the degradation of specular reflection should be investigated, such as the affinity of gas molecules for channel walls. The variation of gas permeability as a function of confinement and temperature should also be measured for both specular and diffuse reflection. In parallel with the experimental work, more simulations or theoretical work that consider quantum effects are needed, to quantitatively understand and predict the properties of frictionless gas transport.

Such research potentially offers comprehensive insight into the nature of gas transport through channels and at low pressures. Knowledge of such gas transport has found extensive application in studies of the aerodynamics of space vehicles, in micro-electromechanical systems, and in shale-gas extraction[7,8]. Further research might also shed light on how laminar membranes can be made from 2D materials for separating mixtures of gases, thereby improving separation efficiency while reducing energy consumption[9]. Finally, frictionless gas transport through channels that are asymmetrically constricted[10] could enable gas-flow rectification[11], a process that might allow the development of new pumps, valves and other devices for controlling gas flow. ■

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1. Keerthi, A. *et al. Nature* **558,** 420–424 (2018).
2. Esfandiar, A. *et al. Science* **358**, 511–513 (2017).
3. Radha, B. *et al. Nature* **538**, 222–225 (2016).
4. Geim, A. K. & Grigorieva, I. V. *Nature* **499**, 419–425 (2013).
5. Holt, J. K. *et al. Science* **312**, 1034–1037 (2006).
6. Majumder, M., Chopra, N. & Hinds, B. J. *ACS Nano* **5**, 3867–3877 (2011).
7. Wu, L. *et al. J. Fluid Mech.* **822**, 398–417 (2017).
8. Shen, C. *Rarefied Gas Dynamics: Fundamentals, Simulations and Micro Flows* (Springer, 2005).
9. Liu, G., Jin, W. & Xu, N. *Angew. Chem. Int. Edn* **55**, 13384–13397 (2016).
10. Zhang, P. & Hung D. *J. Appl. Phys.* **115**, 204908 (2014).
11. Groisman A. & Quake, S. R. *Phys. Rev. Lett.* **92**, 094501 (2004).

STEM CELLS

# Intestinal-niche conundrum solved

**The cellular microenvironment required to sustain adult intestinal stem cells has long been controversial. Cells that release proteins needed for intestinal-tissue renewal have now been defined.** See Letter p.449

LINDA C. SAMUELSON

The human small intestine and colon are maintained throughout life by tissue-resident stem cells, which renew the gut lining at an astounding rate by generating billions of cells every day. The self-renewal, proliferation and differentiation of these intestinal stem cells are prompted by molecular signals from nearby cells called niche cells. Over the past decade, stem-cell biologists have debated the identity of the intestinal niche cells[1]. Two papers in *Nature* (one by Shoshkes-Carmel *et al.*[2] published earlier this year, and the other by Degirmenci *et al.*[3] on page 449) now identify a niche-cell population that provides a signal essential for stem-cell renewal.

Intestinal cells are arranged in a strict spatial layout. Stem cells are found at the base of pit-like structures in the gut wall, called crypts (Fig. 1). They produce highly proliferative progenitor cells, which differentiate into the various mature epithelial-cell types that make up the gut lining as they move away from the crypt base.

By contrast, Paneth cells are differentiated epithelial cells that move down from the progenitor zone to the crypt base. The close physical association between Paneth cells and stem cells has led to the proposal that Paneth cells have niche function, promoting stem-cell self-renewal. Providing support for this idea, a study has shown that Paneth cells enhance intestinal stem-cell growth in culture, and that intestinal stem-cell numbers are reduced in mice in which Paneth-cell numbers are artificially depleted[4]. However, other studies have come to the opposite conclusion, showing normal stem-cell function after Paneth-cell loss[5,6]. Furthermore, Paneth cells are not normally found in colonic crypts. Thus, the status of Paneth cells as niche cells is controversial.

Searching for cells that produce the telltale proteins that promote stem-cell self-renewal is one way of identifying the niche-cell population. The main signalling pathways for