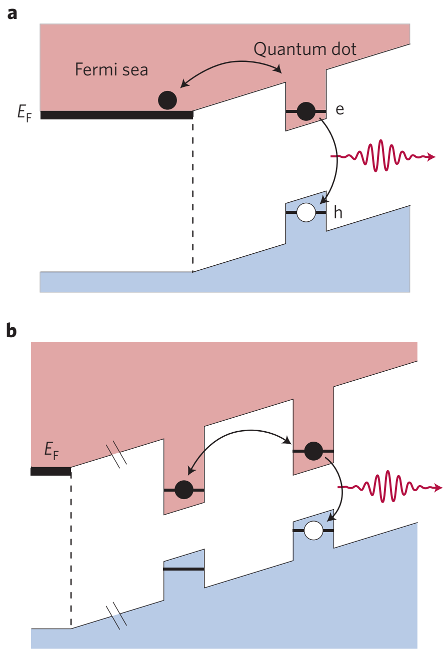

Figure 1 | Coherent tunnelling of an electron into a quantum dot. **a**, The optical recombination spectrum (red arrow) of an electron (e) and hole (h) in a quantum dot is strongly affected by coherent tunnelling (black arrow) between the dot and the Fermi sea. The Fermi energy is denoted by E_F. **b**, The spectrum is similar to that for tunnelling between two dots, except for the absence of shake-up effects.

range, tunnelling is prevented by Coulomb blockade and the one-electron state of the dot is stable. However, at the edge of the stability range the electron state is resonant with the Fermi level and the electron will tunnel back and forth. Such behaviour has been a problem in many recent spin-pumping experiments because this exchange process with the reservoir leads to spin relaxation[2]. Typically the spacer layer is large enough that tunnelling is incoherent. Kleemans *et al.* now find that with a 16 nm spacer the energy of the eigenstate evolves continuously from one charge state to the next — evidence of coherent tunnelling.

Interpreting the emission spectrum from this structure has been aided by previous investigations on so-called quantum-dot molecules — where coherent tunnelling between two closely spaced quantum dots occurs (see Fig. 1b)[3–5]. Spin singlet and triplet states are formed in the limit where there is one hole and two electrons spread between the two dots. Coherent tunnelling leads to an energy shift of the singlet relative to the triplet states — a spin exchange energy in the three-particle problem. In fact this physics is the basis for external control of the electron spin. Laser fields can be used to measure and control the spin states[6].

Kleemans and co-workers now replace the few-particle quantum dot with a degenerate electron gas. Remarkably the hybrid system has a spectrum very much like the singlet of the quantum-dot molecule. The main difference seems to be that the spectral lines are asymmetrically broadened — an effect arising from the shake-up in the electron sea during the optical transition. Kleemans *et al.* note that in this many-body limit there is a state that is shifted out of the continuum to form a 'bound state'. They identify this as a hybrid exciton in analogy to the theoretical model describing the interaction of a discrete spin with an electron gas continuum[7]. It is expected that at temperatures lower than the 4.2 K used in the present experiment, this state should develop into a many-body singlet state — the Kondo exciton state. Such a Kondo state has not been observed yet but occupies the minds of experimentalists as a possibility to observe a tunable Kondo effect in excited states of solids and also as a possibility to coherently control a spin state of an exciton electrically using the metal contact.

This study illustrates once again that quantum size effects can be tailored to engineer the functionality of semiconductor quantum-dot systems. One of the most active present engineering goals is to make a quantum dot serve as a qubit in a quantum computer. To this end there is the need to engineer the structure so that the spin can be precisely controlled through external applied fields. On the other hand there is the need to understand how the electron in the quantum dot interacts with its fluctuating environment. The interaction with the electron reservoir is one good example of this.

Improvements in materials and in measurement continue to drive forward the study of the smallest quantum-confined semiconductor system, the quantum dot. As this effort goes on we will learn to understand its properties, perhaps in terms of old but powerful physics models, such as the Mahan exciton and the Kondo effect, or perhaps in terms of new ones. At the same time we will learn to engineer and take advantage of its quantum properties. ❐

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FLUID DYNAMICS

Propelled by diffusion

The process of diffusion isn't usually expected to be able to generate useful work. But when a neutrally buoyant wedge object is placed in a fluid with a vertical density gradient, the diffusion-driven flow of material can indeed generate a measureable horizontal propulsion.

Michael A. Page

If you place a simple toy boat on a still lake, on a windless day, you would not expect it to move much — unless it has a motor, of course. But many might be surprised to learn that if you were to submerge a similarly motorless toy submarine in salty water it may spontaneously begin to move. Such motion is not random but directed, and has its origins in the little-known phenomenon of diffusion-driven flow that was discovered over 40 years ago in the context of a density-stratified fluid near a sloping boundary[1,2]. Writing in *Nature Physics*, Allshouse and colleagues[3] report an

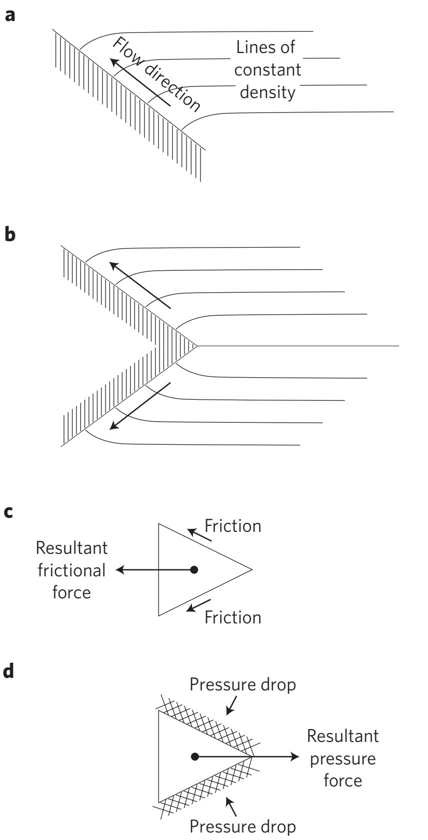

Figure 1 | The effects of diffusion-driven flow. **a**, When a thermally insulating sloped boundary cuts across a thermal gradient in a fluid, it locally modifies the lines of equal temperature. This causes regions of differing buoyancy to exist at the same depth, which drives the fluid up the slope. **b**, Similar flow and density behaviour near a wedge-shaped object. **c**, The frictional forces acting on each face of the submerged object produce a resultant force to the left. **d**, The associated localized pressure drop near the sloping faces produce a resultant force to the right.

intriguing twist on this phenomenon. They find that when a neutrally buoyant wedge is carefully lowered into a bath of salty water with a stable continuous density gradient, it will begin to move horizontally at the level of its buoyancy point — albeit slowly, at a rate of about 1 cm h^{-1} — in the direction of its tip. The same would also happen with the toy submarine, provided it was not symmetric.

Examples of steady, stable, self-propelled motion such as that found by Allshouse *et al.* are rare. The principles that underlie it were originally described in separate papers by Wunsch[1] and Phillips[2] in 1970. Key to this behaviour is how a stable density field can be modified in the vicinity of a sloping solid boundary.

The same principles apply for any source of density variations but the effect is perhaps most easily understood when the variations result from a stable, stratified temperature gradient, with cooler fluid at the bottom and warmer fluid at the top. When a sloping boundary made from a thermally insulating material cuts across such a gradient, it causes the lines of equal temperature and therefore density to bend towards it (Fig. 1a). The resulting buoyancy gradient close to the boundary drives the flow of material up the slope, through the tendency of gravity to flatten the lines of constant density towards the horizontal. Wunsch[1] and Phillips[2] described this behaviour in the context of deep ocean flows and the transport of minerals in water-filled rock fissures, respectively, but it may also play a role in many other natural phenomena including the melting of icebergs[4] and the migration of tectonic plates[5].

The same principles also apply to submerged boundaries. On the upper face of an insulating wedge-shaped object, for example, the insulating surface increases the temperature of the nearby fluid above its original value at the same horizontal level. This relatively warm fluid then rises through its enhanced buoyancy. Frictional effects, from the viscosity of the fluid, balance this acceleration and a steady upslope motion is maintained within a narrow layer close to the sloping surface (Fig. 1b). On the lower face of the wedge the opposite effect occurs, with the fluid adjacent to the insulating surface being cooler than elsewhere at the same level, so that it moves steadily down the sloping surface in that case.

This induced fluid motion above and below the wedge generates two types of force on that object. The first is the frictional force generated as a viscous fluid flows along a surface — which produces a leftwards force in the situation described in Fig. 1c. And the second, which represents an important additional factor recognized by Allshouse and colleagues, is a force generated by the localized pressure drop that occurs along both of the sloping faces, arising from the nearby temperature changes — this acts towards the right in Fig. 1d. The experiments and numerical calculations by Allshouse *et al.* show that the latter effect is stronger for a stationary wedge-shaped object, so that it will accelerate to the right until it reaches the constant speed for which the two forces are in balance.

The energetics of the motion are also worthy of comment; a naive misinterpretation might suggest that the object was in 'perpetual motion', and therefore in violation of the laws of thermodynamics. In fact, as the authors note, the induced fluid motion and the associated acceleration of the submerged body both drawing on the background potential energy of the stable density-stratified fluid. In the absence of any compensating energy flux across the base and top of the tank, the density variations in the fluid will slowly diminish and eventually its density will become constant everywhere.

As the authors indicate, their observations raise several questions. What happens when the body is floating on a free surface in similar situations? Can careful heating of the surface of a submerged body generate similar effects? Does the phenomenon scale up, and could it be used as a mechanism for silent propulsion? Following initial interest in Wunsch's and Phillips's original discovery for a sloping boundary, geophysical applications of such flows have not been pursued, presumably because that motion would be overwhelmed by more dominant factors in a gently stratified and turbulent ocean. However, the new twist of applying similar principles to submerged bodies, perhaps even in controlled micrometre regimes with strong temperature gradients imposed, could extend the breadth of potential applications. ❐

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