countries in the world. Mitigation of this fundamental conflict[3,13] must be a priority for any lion conservation strategy in Africa.

Craig Packer*†, Dennis Ikanda†,
Bernard Kissui*†, Hadas Kushnir*

*Department of Ecology, Evolution and Behavior, University of Minnesota, St Paul, Minnesota 55108, USA
e-mail: packer@cbs.umn.edu
†Tanzania Wildlife Research Institute, Box 661, Arusha, Tanzania

1. Kellert, S. R. *et al. Conserv. Biol.* **10,** 977–990 (1996).
2. Wilson, C. J. *Mammal Rev.* **34,** 211–232 (2004).
3. Ogada, M. O., Woodroffe, R., Oguge, N. O. & Frank, L. G. *Conserv. Biol.* **17,** 1521–1530 (2003).
4. Patterson, B. D., Kasiki, S. M., Selempo, E. & Kays, R. W. *Biol. Conserv.* **119,** 507–516 (2004).
5. Treves, A. *et al. Conserv. Biol.* **18,** 114–125 (2004).
6. Kerbis-Peterhans, J. C. & Gnoske, T. P. J. *East Afric. Nat. Hist.* **90,** 1–40 (2002).
7. Löe, J. & Röskaft, E. *Ambio* **33,** 283–288 (2004).
8. Chardonnet, P. *Conservation of the African Lion: Contribution to a Status Survey* (International Foundation for the Conservation of Wildlife, France, and Conservation Force, USA, 2002).
9. Bauer, H. & Van Der Merwe, S. *Oryx* **38,** 26–31 (2004).
10. Rushby, G. C. *No More the Tusker* (W. H. Allen, London, 1965).
11. Nicholson, B. *The Last of Old Africa* (Safari, Long Beach, California, 2001).
12. TRAFFIC. *Food For Thought: The Utilization of Wild Meat in Eastern and Southern Africa* (IUCN/WWF, Cambridge, UK, 1998).
13. Treves, A. & Karanth, K. U. *Conserv. Biol.* **17,** 1491–1499 (2003).

BROWNIAN MOTION

Absolute negative particle mobility

Noise effects in technological applications, far from being a nuisance, can be exploited with advantage — for example, unavoidable thermal fluctuations have found application in the transport and sorting of colloidal particles[1–3] and biomolecules[4–6]. Here we use a microfluidic system to demonstrate a paradoxical migration mechanism in which particles always move in a direction opposite to the net acting force ('absolute negative mobility') as a result of an interplay between thermal noise, a periodic and symmetric microstructure, and a biased alternating-current electric field. This counterintuitive phenomenon could be used for bioanalytical purposes, for example in the separation and fractionation of colloids, biological molecules and cells.

Newton's second law would seem to exclude absolute negative mobility as a response by a system at rest to a static force. However, such paradoxical behaviour has been experimentally observed in semiconductor devices[7] and theoretically predicted in simplified stochastic model systems[8,9]. Nonlinear dynamics are necessary to reconcile absolute negative mobility with Newton's law, and the system needs to operate far from equilibrium to avoid conflict with the second law of thermodynamics.

To provide a proof-of-principle for absolute negative mobility in a lab-on-a-chip, we designed a simple microfluidic device consisting of periodically arranged posts with alternating small and large gaps (Fig. 1; for methods, see supplementary information). The device is filled with negatively charged beads in an aqueous buffer. Electric fields are generated by applying a voltage along the x-axis, so that a positive voltage generates a positive force on the beads along the x-axis. Applying an alternating voltage, $U_{AC}(t)$, that switches periodically between $\pm U_0$, there is no net motion of the beads for symmetry rea-

sons. This set-up represents our unperturbed non-equilibrium system at rest. But what will be the average migration velocity v in the x direction in response to a static perturbation voltage, U_{DC}, superimposed on $U_{AC}(t)$?

To answer this question, we computed the electric field in the microstructure and, including thermal-noise effects, simulated the bead motion by stochastic differential equa-
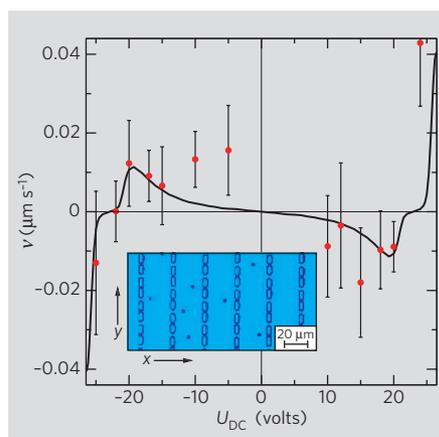

Figure 1 | Absolute negative mobility of polystyrene beads. Movement of 2-μm polystyrene beads in response to a static voltage, U_{DC}, superimposed to an alternating-current voltage that switches between ± 30 V every 25 s. Red dots: experimentally measured velocities, averaged over 40 beads and 200 s. Error bars are of statistical origin, but variabilities in the beads and microstructures also contribute. The line shows the theoretical response characteristics obtained from numerical simulations. Inset: partial view (optical micrograph image) of the poly(dimethylsiloxane) microstructure showing the rectangular posts and migrating beads (dark dots). In both the x and y directions, the gaps between the posts are alternately smaller and larger than the bead diameter. For movie, see supplementary information.

tions, adapted quantitatively to the microstructure geometry and the experimentally determined free diffusion and mobility of the microbeads (see supplementary information). The key feature of the resulting response curve (Fig. 1) is the negative slope that is symmetrical around the origin — a distinct and unambiguous signature of absolute negative mobility. We also measured the average bead velocity by tracking the beads using real-time video microscopy for different values of U_{DC} (see supplementary information) and found that the measured experimental response was in good agreement with theory (Fig. 1).

To explain how absolute negative mobility occurs, we consider the small gaps in the microstructure as 'traps' — electrical field lines can pass through them but the beads cannot. For $0 < U_{DC} < U_0$, the alternating total voltages $\pm U_0 + U_{DC}$ yield a back-and-forth motion of the beads along the x direction. Whenever a bead succeeds in passing through a large gap, it is trapped by the adjacent small gap in the x direction (Fig. 1, inset), unless it thermally diffuses sufficiently far in the y direction to proceed through another large gap. The smaller the voltage, the more time it has to do so and the farther it gets before being trapped. As $|+U_0 + U_{DC}| > |-U_0 + U_{DC}|$, the bead becomes trapped after moving forwards a short distance when $+U_0 + U_{DC} > 0$, whereas it travels backwards for a longer distance when $-U_0 + U_{DC} < 0$, resulting in absolute negative mobility.

We find that this response by a particle is very sensitive to particle size, even to the extent of allowing particles of different sizes to be steered in opposite directions (our unpublished results). Absolute negative mobility therefore holds promise for bioanalytical applications, for example in the sorting of cells, organelles and biochemical compounds.

Alexandra Ros*, Ralf Eichhorn†, Jan Regtmeier*,
Thanh Tu Duong*, Peter Reimann†,
Dario Anselmetti*

*Experimental Biophysics & Applied Nanosciences, and †Condensed Matter Theory, Bielefeld University, 33501 Bielefeld, Germany
e-mail: alexandra.ros@physik.uni-bielefeld.de

1. Rousselet, J., Salome, L., Ajdari, A. & Prost, J. *Nature* **370,** 446–448 (1994).
2. Faucheux, L. P. & Libchaber, A. *Faraday Trans.* **91,** 3163–3166 (1995).
3. Marquet, C., Buguin, A., Talini, L. & Silberzan, P. *Phys. Rev. Lett.* **88,** 168301 (2002).
4. Han, J. & Craighead, H. G. *Science* **288,** 1026–1029 (2000).
5. Bader, J. S. *et al. Proc. Natl Acad. Sci. USA* **96,** 13165–13169 (1999).
6. Huang, L. R., Cox, E. C., Austin, R. H. & Sturm, J. C. *Analyt. Chem.* **75,** 6963–6967 (2003).
7. Keay, B. J. *et al. Phys. Rev. Lett.* **75,** 4102–4105 (1995).
8. Eichhorn, R., Reimann, P. & Hänggi, P. *Phys. Rev. Lett.* **88,** 190601 (2002).
9. Cleuren, B. & Van den Broeck, C. *Phys. Rev. E* **67,** 055101 (2003).