

the drives, precise control of each qubit pair was possible, making all single-excitation states accessible. With this capability, Zanner et al. could produce the non-local dark state on demand and demonstrate coherent control of the ground and dark states. This constitutes an unprecedented degree of manipulation of subradiant states.

With an increased number of qubits, platforms like that of Zanner et al. could be the basis for several quantum technologies. Quantum information arriving in flying photons can be stored in the form of collective excitations with lifetimes that are not limited by those of their constituent qubits. Moreover, dark states are the basis of quantum computation using ‘decoherence-free subspaces’⁷, where a logical qubit is encoded into a superposition state of many physical ones. If that encoding is done using dark states, the logical qubit lifetime may be extended by orders of magnitude. Finally, the enhanced emission of bright states could improve the performance of quantum state readout.

The field of waveguide quantum electrodynamics is a new frontier of quantum systems. Zanner et al. have made strides towards understanding multi-excitation states in this platform by investigating the two-excitation subspace. Its structure reveals that superconducting qubits are better described as anharmonic bosons rather than simplified two-level systems, which is frequently overlooked in the literature. Their tools for coherent control could lead to the discovery and characterization of few-excitation states with exotic quantum statistics^{8,9}. Research in this direction is particularly exciting, as it may produce many-body long-lived states with computational or metrological advantage due to entanglement. Going further, Zanner and co-workers’ methods could be used to realize important theoretical models, such as those with strong photon–photon interactions or that feature many-body localization. This would fulfil waveguide quantum electrodynamics’ promise as a platform

for studying many-body dissipative quantum systems. □

Stuart J. Masson and
Ana Asenjo-García  

Department of Physics, Columbia University,
New York, NY, USA.

✉e-mail: ana.asenjo@columbia.edu

Published online: 14 March 2022
<https://doi.org/10.1038/s41567-022-01571-6>

References

- Zanner, M. et al. *Nat. Phys.* <https://doi.org/10.1038/s41567-022-01527-w> (2022).
- Guerin, W., Araujo, M. O. & Kaiser, R. *Phys. Rev. Lett.* **8**, 083601 (2016).
- Ze, Y. et al. *Phys. Rev. Lett.* **125**, 213602 (2020).
- Ferrioli, G. et al. *Phys. Rev. X* **11**, 021031 (2021).
- Solano, P. et al. *Nat. Commun.* **8**, 1857 (2017).
- Mirhosseini, M. et al. *Nature* **569**, 692–697 (2019).
- Paulisch, V., Kimble, H. J. & González-Tudela, A. *New J. Phys.* **18**, 043041 (2016).
- Albrecht, A. et al. *New J. Phys.* **21**, 025003 (2019).
- Ke, Y. et al. *Phys. Rev. Lett.* **123**, 253601 (2019).

Competing interests

The authors declare no competing interests.



BIOPHYSICS

The power of parasite collectives

Plasmodium sporozoites can move in rotating vortices owing to their chiral shape and mechanical flexibility, revealing important physical aspects of collective motion.

Iva M. Tolić and Isabelle Tardieux

To perpetuate itself, the tiny micrometre-sized parasitic microbe named *Plasmodium* has evolved a strategy of colonizing and proliferating in two distinct animal types, namely mosquitoes and vertebrates, including humans. Whereas the mosquito’s reproductive fitness and life expectancy are barely affected by these parasites, humans pay an enormous price, with malaria annually affecting more than 200 million people and causing over 400,000 deaths¹.

The transmission of *Plasmodium* sporozoites relies on their ability to transition from their mosquito to their vertebrate hosts when the former suck blood from the latter. Remarkably, only a few tens of sporozoites are inoculated individually along with the saliva fluid of the mosquito into the skin of the vertebrate², yet they must then navigate the biomechanically complex environment of the skin, before entering

the blood capillaries and continuing to the liver. Writing in *Nature Physics*, Patra and colleagues carefully examine how the mechanical properties of these parasites can profoundly influence their individual and collective dynamics³.

Intravital microscopy of individual sporozoites gliding through the elastic dermal layer has revealed a striking flexibility^{4–6}, yet little attention has been given to their mechanical properties. By squeezing high concentrations of sporozoites from mosquito salivary glands onto glass coverslips, Patra et al. have designed a clever *ex vivo* setting to address this unsolved issue. Under these conditions, the authors find that the aggregated sporozoites form rotating vortices, in line with the circling patterns of *Plasmodium* previously imaged in salivary glands⁷. Looking at several vortices at once, one can see that the tightly aligned crescent-shaped sporozoites always rotate in the same ‘front-first’ direction

around a common centre — an example of chiral collective motion.

Plasmodium vortices are reminiscent of other spectacular collective motions observed in certain animals and bacteria (Fig. 1a). Rotating vortices often arise when these move towards an attractant — such as food supply or pheromone trails — while avoiding collision with neighbours. They can also be driven by the repulsion from external spatial or predatory constraints. Perhaps most intriguingly, vortices can also emerge from direct ‘social’ interactions between individual animals, including humans, typically based on sound and vision, where isolated individuals tend to move towards a crowd, and those in a crowd avoid collisions by aligning themselves with their neighbours. Therefore, a variety of mechanisms and fitness strategies have been associated with rotating vortices and reflect the huge diversity of vortex scales and samples⁸.

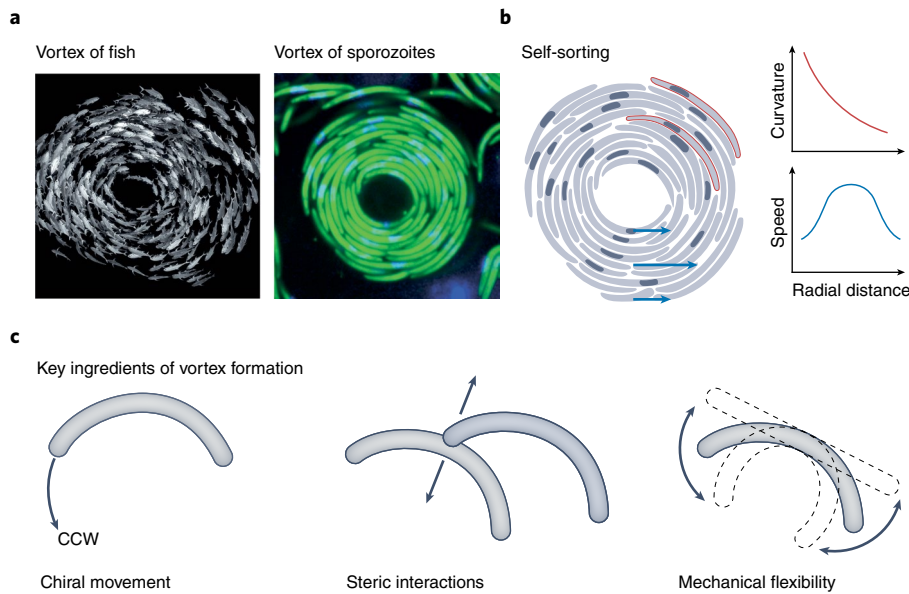


Fig. 1 | Chiral shape and flexibility drive the vortices of *Plasmodium* sporozoites. **a**, Vortices are widespread in biology, from fish to *Plasmodium* sporozoites. **b**, Sporozoites in a vortex undergo self-sorting according to the curvature and speed. The most curved sporozoites move towards the core and the straightest ones to the outer edge. The fastest sporozoites are found in the middle layers. **c**, A vortex arises owing to the chiral (anticlockwise) movement of sporozoites, steric interactions between neighbouring individuals, and their mechanical flexibility. Images in panel **a** reproduced from: Alex Mustard/Nature Picture Library/Science Photo Library (left), ref. ³, Springer Nature Ltd (right).

Plasmodium has evolved its own vortex ‘recipe’, which neither relies on attraction nor external repulsion. This makes sense because the sporozoites have to migrate as individuals once in the skin, and suggests that direct physical interactions must have a dominant role. Indeed, Patra et al. demonstrate that vortex formation and stability is primarily determined by the combination of self-propulsion, curved shape, chirality and mechanical flexibility.

Individual sporozoites glide on a substrate in a circle owing to their curved shape. They display a strong preference for the anticlockwise direction, because the chiral shape of the sporozoite’s microtubule cage dictates the orientation of the secretory organelles of proteins necessary for adhesion and motility⁹.

This inherent anticlockwise gliding of single sporozoites translates into the joint rotation of multiple sporozoites in a vortex. But what makes them aggregate in vortices and how do individual sporozoites find their place within a vortex? Patra

et al. tackled this question by quantitative analysis of sporozoite movements within the vortices, combined with elegant agent-based simulations in which each sporozoite is modelled as a chain of nodes linked by linear and angular springs describing its length and curvature, and neighbouring sporozoites experience repulsion owing to steric interactions.

The experiments showed that sporozoites within a vortex are not all equal: those close to the core are more bent and they run in smaller circles than those at the outer edge (Fig. 1b). Moreover, the fastest sporozoites are found in the middle between the two edges (Fig. 1b). How does this self-sorting occur? It could be that the cells with intrinsically higher curvature end up at the core or that high mechanical flexibility of the sporozoites — which is reflected in marked changes of their shape on interaction with other sporozoites — account for these differences in curvature.

Interestingly, computer simulations showed that inherently chiral movement

of each sporozoite and the flexibility and steric interactions between them are sufficient to generate a vortex (Fig. 1c), whereas differences in intrinsic speed and curvature are not required. In the case when all sporozoites have the same intrinsic curvature and speed, different curvatures in a mature vortex are a consequence of mechanical flexibility. When heterogeneity in propulsion force and curvature is included in the model, the slowest sporozoites are swept away to the inner and outer edges. The curvier ones end up at the inner edge and the straightest ones at the outer edge. Sorting can also happen as a consequence of chirality.

Beyond deepening our understanding of the co-evolutionary processes between the *Plasmodium* parasite and its divergent hosts, the work of Patra and colleagues reveals the role of physical aspects such as geometry, chirality and mechanical flexibility in collective motion. The *Plasmodium* sporozoites are an ideal model system because there are no complications arising from social interactions or complex shapes. The discovery of a new mechanism of collective vortex motion should also bring inspiration for technical applications such as the design of multipurpose vortex-powered microrobot swarms that self-organize and move in a chosen direction¹⁰. □

Iva M. Tolić¹ and Isabelle Tardieux²✉

¹Division of Molecular Biology, Ruđer Bošković Institute, Zagreb, Croatia. ²Institute for Advanced Biosciences, Cnrs UMR 5309, Inserm U 1209, Univ. Grenoble Alpes, Grenoble, France.

✉e-mail: isabelle.tardieux@inserm.fr

Published online: 13 May 2022
<https://doi.org/10.1038/s41567-022-01554-7>

References

1. *World Malaria Report 2017* (World Health Organization, 2017).
2. Frischknecht, F. et al. *Cell Microbiol.* **6**, 687–694 (2004).
3. Patra, P. et al. *Nat. Phys.* <https://doi.org/10.1038/s41567-022-01583-2> (2022).
4. Vanderberg, J. P. & Frevert, U. *Int. J. Parasitol.* **34**, 991–996 (2004).
5. Amino, R. et al. *Nat. Med.* **12**, 220–224 (2006).
6. Hopp, C. S. et al. *eLife* **13**, e07789 (2015).
7. Wells, M. B. & Andrew, D. J. *mBio* **10**, e01238–19 (2019).
8. Delcourt, J., Bode, N. W. & Denoël, M. *Q. Rev. Biol.* **91**, 1–24 (2016).
9. Kudryashev, M. et al. *Cell Microbiol.* **14**, 1757–1768 (2012).
10. Xie, H. et al. *Sci. Robot.* **4**, eaav8006 (2019).

Competing interests

The authors declare no competing interests.