QUANTUM PHYSICS

Noise put to use

Through stochastic resonance, noise-driven fluctuations make an otherwise weak periodic signal accessible. Experiments have now reported quantum stochastic resonance, which arises from intrinsic quantum fluctuations rather than external noise.

Stefan Ludwig

Noise is usually perceived as something negative — just think of electronic noise obscuring signal transmission. At the same time, random fluctuations induced by noise are an integral and important element of nature, and even life. Under non-equilibrium conditions, they may even become a driving force — as happens for the ratchet mechanism, which turns fluctuations into directed motion[1]. Another remarkable noise-driven phenomenon is stochastic resonance[2], where irregular fluctuations can amplify the effect of an otherwise weak signal. Originally introduced in Earth science to model the recurrence of ice ages[3], stochastic resonance has been observed and explored in a broad range of fields, including nonlinear optics, solid-state physics, biology, and even medicine[2]. In most examples, the fluctuations driving stochastic resonance arise from classical sources of noise in the surrounding environment. Now, writing in *Nature Physics*, Timo Wagner and co-authors report the realization of a textbook example of a quantum version of stochastic resonance[4,5], where the defining fluctuations are not caused by coupling to a noisy environment; rather, they are an intrinsic property of a quantum two-level system[6].

The concept of stochastic resonance is illustrated in Fig. 1. It takes place in bistable systems, represented by the double-well potential (Fig. 1a). Stochastic resonance describes the amplification of the effect of a weak signal owing to noise-driving transitions between the system's two fixed points. Of particular interest is the case where the system is exposed to strong noise peaked at a rate that is twice the modulation frequency of the weak periodic signal, as it can lead to synchronization of the noise-driven transitions with a signal that is too weak to drive transitions itself.

The bistable system used in the experiments of Wagner and co-authors is an artificial molecule — a semiconducting lateral double quantum dot. The fixed points of this bistable system correspond to a single electron occupying either the left or the right dot, illustrated by the two wells of the potential shown in Fig. 1a. An advantage of this nanodevice is its full controllability, which makes it an interesting platform for applications in quantum technologies. The dynamics of the double quantum dot exhibits random fluctuations of the electron hopping between the two dots. The fluctuations might be activated by coupling to external noise or can be restricted to quantum tunnelling through the barrier. In both cases, they can be described by the hopping rate, Γ. The experiment by Wagner and co-authors was realized in a noiseless environment at cryogenic temperatures, where quantum-mechanical tunnelling dominates the dynamics.

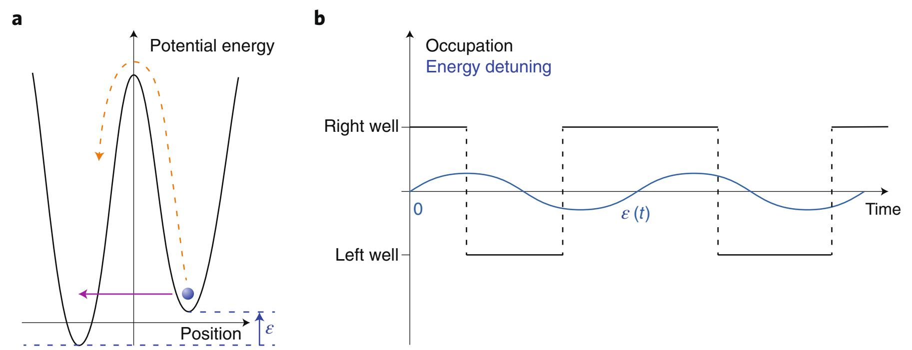

Fig. 1 | Illustration of stochastic resonance. a, A bistable system is illustrated as a particle (blue sphere) in a double-well potential. The potential energy of the particle differs by the detuning ε between the two wells. The particle oscillates between the two wells with a characteristic rate Γ that gives rise to a steady-state-occupation difference between the two wells depending on ε. In the classical limit the oscillation is always caused by energy exchange with the environment (orange dashed arrow), but it can alternatively occur via tunnelling (purple arrow), prevailing the quantum limit. In both cases, the dynamics is probabilistic. **b**, A weak modulation of the detuning, such as $\varepsilon(t) = \varepsilon_0\sin(2\pi f_0 t)$, can cause an oscillation of the momentary steady-state occupation, where the details of the system's dynamics depend on the ratio Γ/f_0. Near the extrema of the modulated $\varepsilon(t)$, the energy difference between the wells makes hopping a little easier in one direction and a little harder in the other. A synchronization between tunnelling and modulation requires $\Gamma \sim 2f_0$, essentially because the particle can only tunnel to the right/left well as long as it occupies the left/right well. In the sketch, stochastic resonance is expressed by the tunnelling events happening near the extrema of $\varepsilon(t)$. However, given their stochastic nature, the exact time of each tunnelling event still fluctuates.

To realize stochastic resonance, the authors applied a weak periodic modulation with frequency f_0 of the energy detuning ε between the two wells, $\varepsilon(t) = \varepsilon_0\sin(2\pi f_0 t)$, of absolute value much smaller than the height of the potential barrier. In the adiabatic limit, for $f_0 \ll \Gamma$, rapid tunnelling through the barrier guarantees a charge distribution according to the momentary potential shape; the average electron position will oscillate between the two wells in phase with the modulation of ε. In the opposite limit, $f_0 \gg \Gamma$, the electron cannot follow the much quicker variations of the local potential, experiencing instead its average value. The most interesting dynamics occurs for $2f_0 \sim \Gamma$, as under this condition the electron typically tunnels twice through the barrier per modulation period. The electron motion then tends to synchronize with the modulation of ε, even if the tunnelling dynamics is incoherent. A hand-waving argument for the appearance of synchronization is that it allows the electron to occupy mostly the lower-lying well, minimizing the system energy.

The lateral double quantum dot used by Wagner and co-authors has the advantage of a wide tunability based on the electric field effect of both Γ and ε. To realize a perfect example of stochastic resonance, they made use of two additional well-established methods. First, they measured the current through a quantum point contact to detect the charge distribution within the double quantum dot[7]. Second, they combined a relatively small tunnelling rate $\Gamma \sim 1$ MHz with a high (20 MHz) bandwidth current measurement to perform real-time charge detection. In this way, they could detect every single tunnelling event and accumulate a full counting statistics for long enough measurement times[8].

As a next step, the authors analysed relevant statistical quantities, such as the number of tunnelling events per period, to achieve accurate information about the system dynamics. In particular, the randomness of the tunnelling events is computed via the Fano factor, calculated as the ratio between the variance and the mean value of the tunnelling distribution function. A Fano factor equal to one indicates a completely stochastic Poisson distribution, whereas a value larger than one points to bunching of tunnelling events. Antibunching corresponds to a Fano factor smaller than one, indicating synchronization between subsequent tunnelling events. Impressively, the authors find a pronounced minimum of this quantity, below one, always centred at $\Gamma = 2f_0$, no matter whether they tune Γ at a fixed modulation frequency f_0 or sweep f_0 for a fixed hopping rate Γ. This is the fundamental characteristic of stochastic resonance.

The role of coherence in the presented experiment remains to be discussed. The dynamics of a quantum system crucially depends on the coherence time — a measure of the speed of the dephasing of the electron's wavefunction. Wagner and co-workers observed stochastic resonance in the incoherent limit, where information on the phase of the electron's wavefunction is lost between successive tunnelling events. It is thanks to decoherence that the stochastic nature of the electron's tunnelling dynamics is indeed maintained. In contrast, the time evolution of the probability function of a fully coherent system is deterministic and, if weakly modulated at $2f_0 \sim \Gamma$, it would show coherent Rabi oscillations of the double-well occupation with a Fano factor much smaller than one, but not necessarily synchronized with the modulation frequency.

With their experiment, Wagner and co-authors have realized a textbook example of stochastic resonance based on quantum tunnelling. An important difference from classical dynamics is that quantum tunnelling does not require energy exchange with the environment but is an inherent property of the quantum two-state system. This difference allows Wagner and co-authors to report quantum stochastic resonance, a phenomenon that might stimulate new ideas for applications in the incoherent regime, in contrast to fully coherent applications of quantum circuits. An example could be the stabilization of small currents with possible applications for quantum-dot-based current standards. ❐

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ACTIVE NEMATICS

Turbulent beginnings

An inspired experimental approach sheds light on the formation of active turbulence in a system of microtubules and molecular motors. The emergent scaling behaviour takes us a step closer to understanding how activity begets turbulence.

Seth Fraden

A comparison between passive and active liquid crystals reveals dramatic differences. A uniformly aligned passive nematic is in its equilibrium state and will remain aligned unless acted upon by an external force. In contrast, a uniformly aligned active nematic is intrinsically unstable; its director spontaneously bends and the fluid begins to flow, driven solely by the consumption of chemical energy. Writing in *Nature Physics*, Berta Martínez-Prat and co-workers have captured the initial instability in a two-dimensional nematic consisting of bundles of microtubules and their associated kinesin motors deposited on an oil–water interface[1].

The experimental challenge was aligning the active nematic at the beginning of the experiment. In previous studies of this system, the instability, which occurs rapidly, would happen out of sight while the experimenters were loading the samples onto the microscope. To overcome this, the team inserted a straw into the centre of the sample at the oil–water interface, thereby drawing in material and creating radial flows that aligned the microtubules.

The initial state immediately after withdrawing the straw resembled a bicycle wheel with the spokes radiating outward from the hub (Fig. 1a). What followed next was dramatic. First, the aligned microtubule fibres began to undulate as they extended and periodically buckled, leading to a collective instability that resulted in alternating rings of ±½ topological defects in the liquid crystal (Fig. 1b). The +½ defects acted as active quasiparticles that generated flow by propelling themselves forward and reoriented the microtubules into alternating bands of circumferentially