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BROWNIAN MACHINERY IN PHYSICS AND BIOLOGY

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Noise is usually thought of as the enemy of order rather as a constructive influence. For the phenomena of Stochastic Resonance and Brownian motors (and/or molecular motors) random noise plays a beneficial role in enhancing detection and/or facilitating directed transmission of information in absence of biasing forces. By virtue of the second law of thermodynamics the emergence of a stationary, directed transport in periodic structures is *not* possible when only equilibrium fluctuations are acting. The situation changes, however, in presence of additional non-equilibrium fluctuations. The objective centers around the possibility to rectify noise so that quantum and classical objects can be directed around on *a priori* designed routes in biological and physical systems. In doing so, the energy from the haphazard motion of (quantum) Brownian particles is extracted to perform useful work against an external load. This very concept of Brownian motors is elucidated; they carry a prominent potential for applications to separate, pump and direct particles and cargo in various physical systems and play a key role for intracellular transport.

Is it possible to get work out of fluctuations? The answer must be a sure "*yes*". This fact is evident from the daily observation with the functioning of mechanical and electrical rectifiers. A typical realization refers to the self-winding wristwatch that works especially well with gesticulating carriers. It must be stressed, however, that all these examples refer to macroscopic fluctuations. The issue becomes more subtle if microscopic fluctuations of classical or quantum Brownian origin are involved [1 – 8]. In presence of dissipation, this area of research has been in the limelight over recent years and it enjoys a still increasing activity. It is known under the label of *Brownian motors* [1, 3, 7, 8], or *Brownian ratchets*; within a biological context, whereby cargo or protein filaments are moved around in living organisms by motor enzymes, it is referred to as *molecular motors* [1, 5, 8].

Prima facie, this very suggestion that by use of ubiquitous irregular thermal motion in a Brownian motor noise becomes rectified to yield regular, directed transport sounds paradoxical. Such a concept seemingly has a smell that thereby entropy in a closed system can be reduced. Such a result, however, would present a distinct violation of the second law of thermodynamics. Indeed, this challenge of rectifying irregular thermal motion into directed transport does function only if both time – reversal symmetry is broken either by a source of irreversibility far from equilibrium or external driving *and* if an element of asymmetry of either spatial (i.e. ratchet-like) or dynamical origin is present. Then, the generic detailed balance symmetry, which does characterize all thermal equilibrium systems, will become broken. As a result, a finite, stationary directed particle current in periodic structures will generally emerge – unless an intrinsic *supersymmetry*, see in [8], forbids such a transport.

In asymmetric (dissipative) periodic structures driven by thermal noise (which does obey the fluctuation-dissipation theorem of second kind) and a source of unbiased driving far from thermal equilibrium it is therefore the rule – rather than the exception – that *chance becomes channeled.* This implies that a finite transport will occur, which uses the energy source of random thermal noise together with some element of non-equilibrium perturbations (such as unbiased, periodic deterministic driving and/or non-thermal noise of zero average). Put differently, a stationary, noise-induced directed transport emerges in *absence* of any acting constant bias force. As a consequence, with an external bias applied against the direction of this current, the thermal noise in the Brownian motor is able to perform work against an external load; i.e. particles can be transported upwards the potential "hill" from which the bias is derived. The direction of the directed transport is usually not obvious *a priori*; it depends on the details of the set-up and may *change sign* as a function of control parameters such as the temperature, particle mass, friction strength, time-scale and strength of the non-equilibrium perturbation, to name a few. Thereby, the transport generally may pass zero at definite value of some parameter. Note also that such – possibly multiple – *current reversals* occur then not only as a function of one given parameter, such e.g. the temperature, but the very nature of the rectified transport will then imply as well a current reversal as a function of other parameters [7, 8]. Those current reversals are of prime importance for novel technological applications; these form the necessary basis for efficient novel schemes for separating and rerouting particles. For example, a potential application of a Brownian motor consists in the separation of healthy from infected, sick cells, thereby providing cure for patients without the need of using possibly harmful pharmaceutical means.

The author will here not dwell further on the rich physics that these Brownian motors do exhibit. Several excellent reviews [1, 3, 5, 7, 8] and feature articles [2, 4, 6] covering differing aspects of the topic have been written recently. A list of recent publications, which do cover the present state of the art, is provided below together with some illustrative URL's. Moreover, the author is confident that a more detailed study of those feature articles and reviews will likely invigorate some readers in pursuing future, own research is this timely area. A superb and comprehensive review, which I like to recommend highly, has been written recently by Peter Reimann [8]; it can be downloaded from the URL: http://xxx.uni-augsburg.de/abs/cond-mat/0010237.

References

1. Astumian R. D., Thermodynamics and Kinetics of a Brownian Motor, *Science* **276** (1997) pp. 917 - 922.
2. Brooks M., Quantum Clockwork, *New Scientist* **2222** (2000) pp. 29 -31.
3. Hänggi P. and Bartussek R., Brownian rectifiers: How to convert Brownian motion into directed transport. **In**: Nonlinear Physics of Complex Systems – Current Status and Future Trends, J. Parisi, S. C. Müller and W. Zimmermann, eds, *Lecture Notes in Physics* **476** (1996) pp. 294 - 308; (Springer, Berlin, New York, 1996).
4. Hänggi P. and Reimann P., Quantum ratchets reroute electrons, *Physics World* **12** (1999) pp. 21 - 22.
5. Jülicher F., Ajdari A., Prost J., Modeling molecular motors, *Rev. Mod. Phys.* **69** (1997) pp. 1269 - 1281.
6. Leibler S., Moving forward noisily, *Nature* **370** (1994) pp. 412-413.

7. Reimann P. and Hänggi P., Quantum features of Brownian motors and Stochastic Resonance, *Chaos* **8** (1998) pp. 629 - 642.
8. Reimann P., Brownian Motors: noisy transport far from thermal equilibrium, *Physics Reports* (2001); **cond-mat/0010237**.

Useful URL's

For recent publications on Brownian Motors see:

http://www.physik.uni-augsburg.de/theo1/hanggi/Brownian.html

Some insightful simulations can be found on:

http://monet.physik.unibas.ch/~elmer/bm/
http://www.ph.tum.de/~frey/
http://www.physik.TU-Muenchen.de/~avilfan/ecmm
http://www.borisylab.nwu.edu/