Human-Scale Brownian Ratchet: A Historical Thought Experiment

M. Lagoin, C. Crauste-Thibierge, and A. Naert*
Ens de Lyon, CNRS, Laboratoire de physique, F-69342 Lyon, France

(Received 24 April 2022; revised 29 July 2022; accepted 9 August 2022; published 15 September 2022)

We present an experimental realization at macroscopic scale of the storied Brownian ratchet, which is an illustration of the Maxwell's demon. In our mechanism, the rotation of a centimeter-scale 1D Brownian object in a granular gas is detected by an electromechanical converter (dynamo), generating a voltage proportional to its angular velocity. The current generated by this random rotation is rectified by an electronic device (demon), such that only positive current passes. Eventually, work can be produced. The advantage of such a macroscopic setup is to allow measurement of all the observables with time: useful power (work), heat taken from the bath, and finally the efficiency of the equivalent heat engine. The feedback allowing the conversion from heat into work expresses as a bias on the Brownian motion.

DOI: 10.1103/PhysRevLett.129.120606

Introduction.—The second law of thermodynamics, among many other consequences, implies that heat spontaneously flows from high to low temperature bodies [1]. Maxwell was one of the first to sense the statistical nature of these axioms [2]. More precisely, he had the intuition that they should be taken into account only for the averaged observables. We now know that state variables are fluctuating quantities, but it was not the case then. Indeed, the conception of matter as composed of atoms and molecules in random thermal motion was not yet accepted in Maxwell's time. Such considerations were revolutionary and among the very first openings to statistical physics.

To illustrate his point, Maxwell proposed an experiment that would, if performed, contradict the second principle, i.e., a paradox. The principle is as follows. If an imaginary *being* is able to take information on the state of a system (measurement), it can act on this system. For instance, it can sort particles or extract work from heat, at no cost of energy. This being has been later called *Maxwell's demon*. Different versions of this simplistic thought experiment fueled rich and profound discussions for over 150 years. The most famous are the Szilard engine [3], the Brillouin rectifier [4], and the ratchet and pawl [5]. The detailed operation of these devices cannot be discussed here; we refer to the detailed review from Leff and Rex [6].

The paradox of Maxwell's demon was first resolved by Smoluchowski, arguing that no sorting is possible if the demon itself is not at a temperature lower than that of the gas [7]. In other words, Maxwell's demon is actually a heat engine, the cold bath being not apparent at first sight (detailed in Feynman [5]). Looking closer, Maxwell's demon is operating a conversion from information into heat (entropy transferred to a cold bath). The detailed processed was first clarified by Brillouin [4] and Landauer [8], paving the way to the very active field of information thermodynamics [9–11].

Experiments were technically unrealizable in Maxwell's time. They could only be performed in the last decade, thanks to a colloidal Brownian rotor under feedback controlled rotating electric field [12], or a colloid bead oscillating randomly in the simple or double-well potential of optical tweezers [13]. These pioneering experiments made it possible to quantitatively investigate the functioning of Maxwell's demons. They were historically the first to establish the link between information theory and statistical physics. It was later confirmed by other groups with various systems including AFM experiments [14], even at finite time [15]. We present a novel experimental construction of the celebrated "ratchet and pawl" [5]. This is a mechanical realization of a Maxwell's demon, illustrating the arguments of Smoluchowski. In [5], the random torque caused by the collisions with a molecular gas sets a rotor into a 1D Brownian motion. Consider a rectifying mechanical device, like a ratchet and pawl, fixed on its shaft, allowing the rotation in one direction only. In this case, work can be extracted, seemingly from a single heat reservoir, which constitutes a perpetual motion of the second kind. This is the Maxwell's demon paradox. We present here our first measurements in such system, of time-dependent observables like heat and work rate.

The originality of our setup is twofold. First, it is macroscopic, at human scale (centimeter scale). The role of the molecular heat bath is played by a dilute granular gas. D'Anna *et al.* proposed a system somehow comparable, in that a rotor undergoes 1D diffusion in a (dense) granular material [16]. Being dissipative, external power has to be supplied to sustain a nonequilibrium steady state. The granular gas is a *thermostat*, in the sense that it sets a constant effective temperature, written kT. Throughout this Letter, temperature is given in energy units, Joule. The typical value is here $kT \simeq 10^{-7}$ J. Such a value is huge, but consistent with other macroscopic

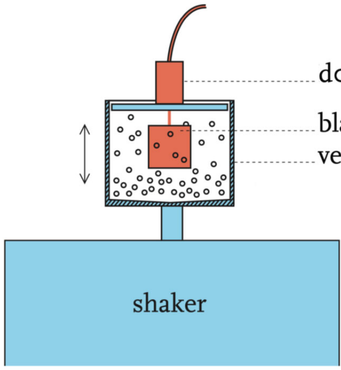

FIG. 1. Sketch of the experimental system. The beads are vibrated vertically in a vessel by an electromagnetic shaker. A blade is immersed in the grains, fastened on the shaft of a small dc motor.

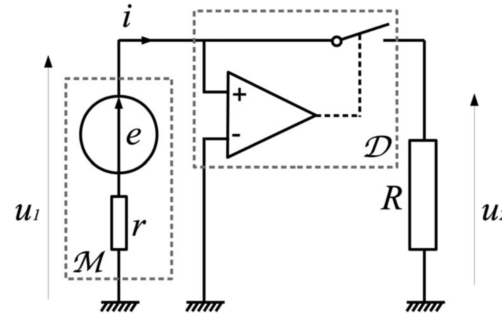

FIG. 2. Electrical circuit associated with the probe. The motor $\mathcal{M}$ is represented in a dashed rectangle by an ideal voltage source e and its internal resistance r. The demon $\mathcal{D}$ is composed of a comparator, at the terminals of the motor, triggering a switch that allows the current to pass or not in the load resistance R, depending on the polarity of u_1.

systems such as in [16]. The way temperature is measured, using consistently the fluctuation dissipation theorem or fluctuation theorem, is detailed in [17]. Second, it makes use of an electromechanical conversion: the rotor's movement is converted into an electrical voltage. In that case, using an electronic rectifying device as demon avoids at once all difficulties linked to mechanical plays and friction.

Experiment.—A centimeter-size rotor is embedded in a granular gas playing the role of heat bath (about 340 stainless steel beads of 3 mm diameter and 0.1 mg mass). Such a macroscopic gas is dissipative, i.e., some power is supplied to balance dissipation on the average and achieve a steady state. The beads are contained in a cylindrical vessel, accelerated vertically at a few gravitational force equivalents (gravitational acceleration) by an electromagnetic shaker (B&K 4809), at a frequency of 40 Hz (see Fig. 1).

A rotating $20 \times 20 \times 0.4$ mm stainless steel blade, immersed in the granular gas, is secured on the shaft of a dc micromotor (Maxon RE10118391), set vertically on the axis of symmetry of the 5 cm diameter cell. The micromotor is simply used as an electromechanical converter (dynamo). The voltage at its terminals is the image of the angular velocity: $e(t) = \alpha\dot{\theta}(t)$, thanks to Faraday induction. The prefactor $\alpha \simeq 0.0095$ V/(rad/s) is characteristic of the device.

The granular gas colliding the blade causes its random rotation, realizing a macroscopic 1D Brownian motion. If the electrical circuit is closed on a load, the fluctuating voltage at the terminals of the motor gives rise to a current $i(t)$. This current is modulated by an electrical Maxwell's demon, composed of a voltage comparator and a switch. Whatever the voltage fluctuations, only one direction of current is allowed: the demon is an electrical rectifier, analog to the usual ratchet and pawl. To avoid spurious transients, we chose a high-speed voltage comparator, with compensated thermal drift (MAX987). It triggers a static switch IC, able to commute within 200 ns (ADG734BRUZ).

The fluctuating ac voltage ultimately gives rise to a rectified current. This dc current can be used to produce work, as, for instance, charging a capacitor or a battery, or even lifting a weight. For convenience, we used here an ohmic resistor $R = 200\ \Omega$ as the load, without changing the principle of the measurement (pictured in Fig. 2).

We record voltages u_1 and u_2 thanks to a NI-PXI4462 24 bits synchronous A/D converter. The induced voltage is $e = u_1 + ri$. The current $i = (1/R)u_2$, caused by e, is flowing into the resistance R whenever the switch is closed. The resistance of this switch in the closed state is $r' \simeq 2.5\ \Omega$, otherwise $r' \simeq \infty$ in the open state (leak current $\lesssim 100$ pA). This electronic demon behaves as a perfect diode (zero voltage threshold).

If $u_1 > 0$, a current flows: $i = (e/R_t)$, where the total resistance in the loop is $R_t = R + r + r'$. The internal resistance of the motor is $r \simeq 120\ \Omega$. It is measured, like R, thanks to an ohmmeter. The current through the motor gives rise to a torque that opposes the rotation (Lenz's law). In other words, when the switch is closed, an ohmic damping adds to the viscous damping of the gas. The ohmic load represents the weight lifted by the winch in the mechanical ratchet described in Feynman's lectures.

The voltage noise $e(t)$, represents the velocity of a rotor in the granular gas (hot bath). To detect properly the sign of the voltage, the thermal (Nyquist) noise of the comparator itself must be much lower than $e(t)$. This is obviously the case at room temperature ($k_B T \simeq 10^{-21}$ J). This is, in electrical words, the expression of the Feynman-Smoluchowski's explanation of Maxwell's paradox: work can be produced because the heat engine is coupled to both a hot bath and a cold bath. The demon stays in the low temperature heat bath.

The demon's choice.—Let us now compare the random rotation with and without the demon. In the latter case, the rotor is subject to the random forcing of the gas, whereas the averaged collisions cause damping (gas viscosity). This equilibrium on average is the essence of the

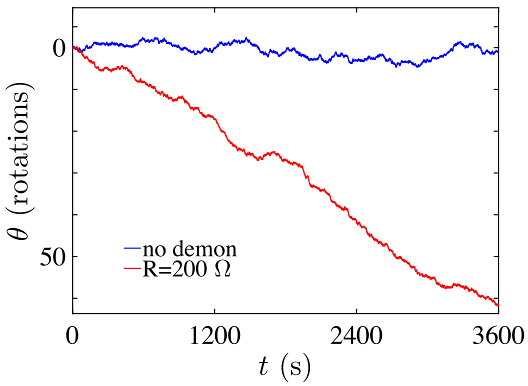

FIG. 3. 1 h time samples of angular trajectories of the rotor, with the demon active (red) or inactive (blue).

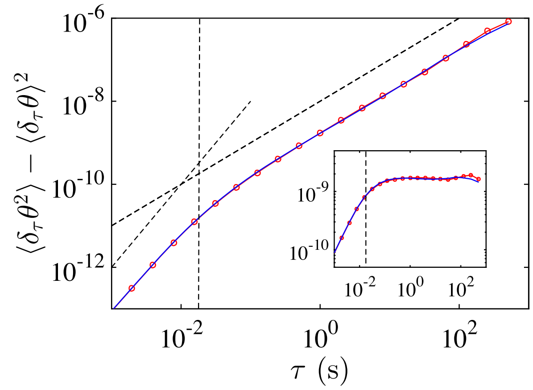

FIG. 4. Variance of the angular increments $\delta_\tau\theta$ over the time-lag τ with demon (red line with symbols) or without (blue line). As an eye guide, doted lines of slopes 1 and 2 are drawn. The inset shows $(1/\tau)(\langle\delta_\tau\theta^2\rangle - \langle\delta_\tau\theta\rangle^2)$ against τ. Vertical dashed lines figure the velocity correlation time, $\tau^* \simeq 18$ ms.

fluctuation-dissipation theorem, taking into account the temperature of the gas [17]. Then, the angle of the rotor remains constant in average (blue trajectory in Fig. 3). When the demon is at work, the symmetry between positive and negative rotation breaks, because ohmic dissipation in R occurs in one direction only. It results in a drift $\langle\dot{\theta}\rangle$ (temporal average). One example is presented in Fig. 3.

Let us now consider the variance $\langle\delta_\tau\theta^2\rangle - \langle\delta_\tau\theta\rangle^2$ of the angular time increments $\delta_\tau\theta(t) = \theta(t+\tau) - \theta(t)$, over a time τ, i.e., the time coarse-grained mean square rotation.

One clearly identifies in Fig. 4 a ballistic and a diffusive regime, where the variance is proportional to τ^2 or τ, for time lags respectively smaller or larger than a crossover time, that it is approximately the correlation time τ^* [18]. The mean time between collisions is about 3 ms, which matches a ballistic regime. The correlation time of the angular velocity is $\tau^* \simeq 18$ ms. Although not very large, this separation of scales is reasonably approximated by a diffusion process. Observing the crossover between both regimes is extremely difficult in a gas [19] or a liquid [20]. Remarkably, $\langle\delta_\tau\theta^2\rangle - \langle\delta_\tau\theta\rangle^2$ has exactly the same time dependance whether the demon is active or not: red and blue lines are exactly superimposed in Fig. 4. It means that the rotor undergoes a similar diffusion process, if considered in a frame of reference rotating at speed $\langle\dot{\theta}\rangle$. Note that the average rotation with the demon is quite small, typically five rotations per hour, it is indeed a tiny perturbation onto the gas. Consistently, the histograms of the rotor's speed are almost the same with or without demon (see Fig. 5).

The fluctuations of velocity in this system are not expected to be Gaussian. It has been shown previously they actually have a stretched exponential distribution, with an exponent $\simeq$1.45, consistently with the literature [21]. On the histograms of Fig. 5, the negative fluctuations are unaffected when switch is open ($\dot{\theta} < 0$). It could be different on the $\dot{\theta} > 0$ side, where the demon causes a very slight depletion, due to the damping of the blade motion by the load. The effect on the velocity histogram is so small it can barely be seen, which means that very little power is extracted, or, in other words, very little perturbation is done by the system on the bath. The overall effect is a slight angular drift under the action of the demon, already mentioned along with Fig. 5. The smallness of the perturbation, $\langle\dot{\theta}\rangle \simeq 0.016$ rps, can be understood in different ways. It confirms that the fluctuations of the rotor are strongly coupled with the dynamics of the beads, and the energy taken from the bath is small, as to be explained below. The bath is a good thermostat for a demon that makes a weak perturbation. The measurements of heat and work rates are discussed in the next section.

Heat, work, and efficiency.—The paradox of Maxwell's demon is explained in the Feynman lectures, by considering the ratchet and pawl system as a heat engine, working between a hot bath on the one hand (here the granular gas at temperature kT), and a cold bath on the other hand (the surroundings). The electronic demon system stands at room temperature (comparator and switch), as well as the load R and the motor. This model heat engine extracts heat from the hot bath and releases part of it into the cold sink, producing some work in between.

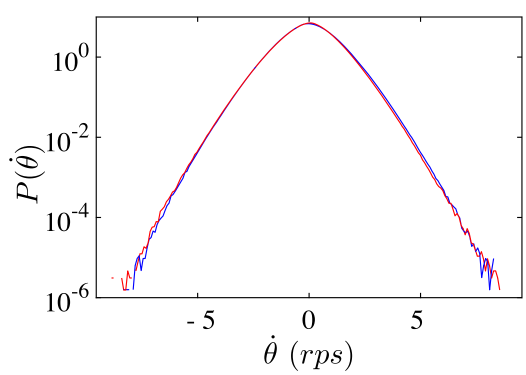

FIG. 5. Histograms of the rotor's speed. A very slight depletion can be seen on the right wing, when the demon is active (red), in comparison to the case where the demon is off (blue).

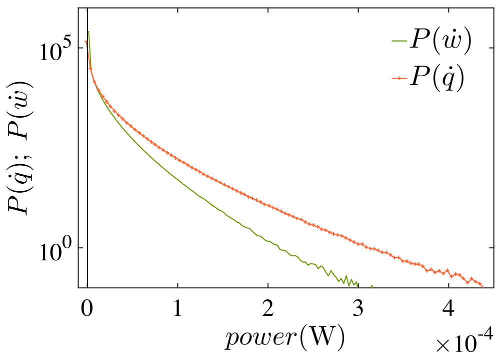

FIG. 6. Normalized histograms of the heat and work per time unit, $\dot{q}$ (orange doted line) and $\dot{w}$ (green line). Averaged heat and work per time unit are $\langle \dot{q} \rangle = \langle ei \rangle \simeq 6.6\ \mu$W and $\langle \dot{w} \rangle = R\langle i^2 \rangle \simeq 4.2\ \mu$W.

Now, let us see the energy balance of this steady state heat engine. Per time unit, $\dot{w} = Ri^2$ represents the work produced thanks to the ratchet heat engine. On the other hand, the heat per time unit extracted from the hot bath is $\dot{q} = ei$. Both histograms show fat tails for positive power fluctuations (see Fig. 6).

Two comments can be made: $\dot{q}$ and $\dot{w}$ are positive, and exhibit a zero most probable value, corresponding to the switch opened. These statistics deserve specific investigation, but that is beyond the scope of this Letter.

Let us consider the averaged quantities. Per time unit, the heat taken from the granular gas is $\langle \dot{q} \rangle \simeq 6.6\ \mu$W, and the work produced is $\langle \dot{w} \rangle \simeq 4.2\ \mu$W. We note again that these values are very small if compared to the power used to keep the granular gas in a steady state, ~10 W, called *house keeping heat* [22]. It is a reliable thermostat.

The efficiency of the heat engine is $\eta = (\langle \dot{w} \rangle / \langle \dot{q} \rangle) \simeq 64\%$. An upper bound for the efficiency corresponds theoretically to a quasistatic process. It is the Carnot efficiency: $\eta_C = 1 - (kT_c/kT_h)$, where kT_c and kT_h are the temperatures of the cold and hot baths, respectively. The temperature of the gas is $kT_h = 1.36 \pm 0.15 \times 10^{-7}$ J, and the room temperature is $kT_c = k_B T_{\text{room}} \simeq 10^{-21}$ J. This leads to $\eta_C \simeq 1 - 10^{-14} \simeq 1$. As expected, $\eta < \eta_C$. The difference is mainly due to the losses. To be specific, it is mostly Joule dissipation: $(r + r')\langle i^2 \rangle \simeq 2.3 \times 10^{-6}$ W.

Discussion.—We designed and produced a macroscopic version of the sometimes-called "Feynman-Smoluchowski ratchet," a thought experiment that allows us to convert heat into work through the action of an information device, a Maxwell's demon. Our setup is operating in contact with a granular gas as heat bath. It makes use of, first, electromechanical conversion, and, second, an electronic device as demon, to replace the traditionally featured mechanical ratchet and pawl system. Granular ratchets have been studied in the past, but, to our knowledge, no measurements were performed on their thermodynamic properties [23]. Our system is profitable in that no friction exists in the demon's part. The only relevant damping effects are the finite impedance of the motor, and in the open and closed states of the switch, easy to take into account. The dissipation in the gas itself is evidently irrelevant. Indeed, as it is merely a source of noise, the dynamics of the rotor is not affected by the dissipation in the beads' collisions. Only the effective temperature matters.

We deliberately chose Smoluchowski and Feynman's take on Maxwell's demon paradox. In that regard, it is a heat engine running between a hot heat bath (granular gas) and a cold one (room). Thanks to this macroscopic approach, we can measure precisely various fluctuating observables, such as, per time unit, the heat extracted from the hot reservoir, and the work performed on a load (here represented by R): $\dot{q}(t)$ and $\dot{w}(t)$. More interesting, our Brownian ratchet gives a direct access to the measurement of the entropy of information. Indeed, some heat is released to the cold sink because of the entropy production in the erasure of the demon's information, as proposed by Brillouin [4]. It can be obtained from the digital triggering signal of the demon, $k_B T \log 2$ per bit of information erased. As it is, at room temperature, this contribution is extremely small, barely measurable (~10^{-19} W on the average). The investigation of this digital signal is in progress.

To conclude, we designed and constructed a system which has never been done before, to our knowledge, that reproduces at macroscale a famous thought experiment illustrating Maxwell's demon. It is a convenient experimental test rig, allowing us to measure any fluctuating observable in a reliable way. We show that the feedback of Maxwell's demon is to bias the random motion. We quantitatively measure the heat and work rates, and calculate the efficiency of the equivalent heat engine.

Besides, from a more practical viewpoint, macroscopic Brownian ratchets typify the very principle of *energy harvesting*, i.e., extracting useful work from fluctuations [24].

We acknowledge F. Ropars for designing and realizing the electronic demon, and also J. Marot. We are grateful to S. Aumaître, A. Archambault, and A. Steinberger, for many fruitful discussions. We also thank M. Adda-Bedia for careful reading and suggestions on the manuscript. And, we thank the ENS-Lyon Physics Laboratory for allowing us to conduct our experiments.

*antoine.naert@ens-lyon.fr

[1] Herbert B. Callen, *Thermodynamics and an Introduction to Thermostatistics*, 2nd ed. (John Wiley & Sons, New York, 1985).

[2] J. C. Maxwell, *Theory of Heat* (Dover, New York, 1871) (republished by Longmans, Green, London, 2001), ISBN 0-486-41735-2.

[3] L. Szilard, über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen, Z. Phys. **53**, 840 (1929) (in German).

[4] L. Brillouin, Can the rectifier become a thermodynamical demon?, Phys. Rev. **78**, 627 (1950).

[5] R. Feynman, *The Feynman Lectures on Physics* (Addison-Wesley Publishing Company, Reading, MA, 1963), Vol. 1, Chap. 46.

[6] *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing*, edited by Harvey S. Leff and Andrew F. Rex (CRC Press, Boca Raton, 2002), ISBN 978-0-7503-0759-8.

[7] M. von Smoluchowski, Experimentell nachweisbare, der üblichen Thermodynamik widersprechende Molekularphänomene, Phys. Z. **13**, 1069 (1912).

[8] R. Landauer, Irreversibility and heat generation in the computing process, IBM J. Res. Dev. **5**, 183 (1961).

[9] T. Sagawa, Thermodynamics of information processing in small systems, Prog. Theor. Phys. **127**, 1 (2012).

[10] J. Parrondo, J. Horowitz, and T. Sagawa, Thermodynamics of information, Nat. Phys. **11**, 131 (2015).

[11] É. Lutz and S. Ciliberto, Information: From Maxwell's demon to Landauer's eraser, Phys. Today **68**, No. 9, 30 (2015).

[12] S. Toyabe, T. Sagawa, M. Ueda, E. Muneyuki, and M. Sano, Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality, Nat. Phys. **6**, 988 (2010).

[13] A. Bérut, A. Arakelyan, A. Petrosyan, S. Ciliberto, R. Dillenschneider, and É. Lutz, Experimental verification of Landauer's principle linking information and thermodynamics, Nature (London) **483**, 187 (2012).

[14] S. Dago, J. Pereda, N. Barros, S. Ciliberto, and L. Bellon, Information and Thermodynamics: Fast and Precise Approach to Landauer's Bound in an Underdamped Micromechanical Oscillator, Phys. Rev. Lett. **126**, 170601 (2021); S. Dago and L. Bellon, Dynamics of Information Erasure and Extension of Landauer's Bound to Fast Processes, Phys. Rev. Lett. **128**, 070604 (2022),

[15] J. Hong, B. Lambson, S. Dhuey, and J. Bokor, Experimental test of Landauer's principle in single-bit operations on nanomagnetic memory bits, Sci. Adv. **2**, e1501492 (2016); A. O. Orlov, C. S. Lent, C. C. Thorpe, G. P. Boechler, and G. L. Snider, The Japan Society of Applied Physics, find out more Experimental Test of Landauer's Principle at the sub-k_BT level, Jpn. J. Appl. Phys. **51**, 06FE10 (2012); Y. Jun, M. Gavrilov, and J. Bechhoefer, High-Precision Test of Landauer's Principle in a Feedback Trap, Phys. Rev. Lett. **113**, 190601 (2014).

[16] G. D'Anna, P. Mayor, A. Barrat, V. Loreto, and Franco Nori, Observing brownian motion in vibration-fluidized granular matter, Nature (London) **424**, 909 (2003).

[17] J.-Y. Chastaing, J.-C. Géminard, and A. Naert, Two methods to measure granular gas temperature, J. Stat. Mech. (2017) P073212.

[18] X. Bian, C. Kim, and G. E. Karniadakis, 111 years of Brownian motion, Soft Matter **12**, 6331 (2016).

[19] T. Li, S. Kheifets, D. Medellin, and M. G. Raizen, Measurement of the instantaneous velocity of a Brownian particle, Science **328**, 1673 (2010).

[20] R. Huang, I. Chavez, K. M. Taute, B. Luki, S. Jeney, M. G. Raizen, and E.-L. Florin, Direct observation of the full transition from ballistic to diffusive Brownian motion in a liquid, Nat. Phys. **7**, 576 (2011).

[21] J.-Y. Chastaing, J.-C. Géminard, and A. Naert, Experimental study of energy exchanges between two coupled granular gases, Phys. Rev. E **94**, 062110 (2016), and references therein

[22] Y. Oono and M. Paniconi, Steady state thermodynamics, Prog. Theor. Phys. Suppl. **130**, 29 (1998); S.-I. Sasa and H.Tasaki, Steady state thermodynamics, J. Stat. Phys. **125**, 125 (2006).

[23] D. van der Meer, P. Reimann, K. V. van der Weele, and D. Lohse, Spontaneous Ratchet Effect in a Granular Gas, Phys. Rev. Lett. **92**, 184301 (2004); A. Gnoli, A. Petri, F. Dalton, G. Pontuale, G. Gradenigo, A. Sarracino, and A. Puglisi, Brownian Ratchet in a Thermal Bath Driven by Coulomb Friction, Phys. Rev. Lett. **110**, 120601 (2013).

[24] A. Khaligh, P. Zeng, and C. Zheng, Kinetic energy harvesting using piezoelectric and electromagnetic technologies—state of the art, IEEE Transactions on Industrial Electronics **57**, 850 (2010).