A STUDY ON BROWNIAN MOTION AND THERMODYNAMICS

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ABSTRACT

Externally generated or chemically reacted nonequilibrium fluctuations are a reason for bias in Brownian motion of a particle in an anisotropic medium without thermal gradients using gravity or macroscopic electric field. The study further evaluates the application of fluctuation-driven transport whereby chemical energy drives the motion of particles and macromolecules. The mechanism is applied in a variety of fields including particle separation and designing of molecular motors and pumps.

Keywords: Brownian motion, Thermodynamics, Fluctuation-driven transport

Introduction

Presence of a small particle in liquid can lead to random collisions added by solvent molecules. Consequently, it can lead to erratic movement, or otherwise Brownian motion, gets illustrated theoretically by Einstein (1) and further independently noted by Langevin (2). According to the hypothesis of Langevin forces over particle caused by solvent is subject to split in 2 determined components, which are-

(i) A fluctuating force changing direction as well as magnitude on a frequently assessed basis for other time scale related to the system as well as averages towards zero, in due course of time, and

(ii) A viscous-drag force that slow down the motions brought by fluctuation.

These are the two forces that never remain independent: Amplitude related to the force of fluctuation gets governed through viscosity related to the solution as well as temperature, in a way that fluctuation gets termed under thermal noise.

At the state of equilibrium, thermal noise’s effect remains symmetric, even under anisotropic medium. The 2nd law noted under thermodynamics demands for- Structural features, irrespective of the way the approach gets designed, and never remain biased to Brownian motion (3, 4).

In order to demonstrate the same, Feynman analysed possibility of implementing thermal noise under conjunction added by anisotropy towards
driving motor in reference to “ratchet and pawl” tool shrunk to the size of microscopic entity (4). According to Feynman, as all the noted components meant for such a device get treated consistently, whereby the net motion never gets attained under isothermal system, irrespective of the anisotropy led by the teeth of ratchet. Still, thermal gradient under synergy added by Brownian motion is liable to cause directed mode of motion over ratchet as well as being implied for respective work. Practically, large amount of thermal gradients remain impossible for maintenance over smaller distances. Especially, in case of chemistry and biology, thermal gradients are liable to drive necessary motion that is unrealistic. It is here that irrespective of pervasive approach, Brownian motion that is not implied to any scope under the mode of separating/moving particles, which can be under natural systems (like biological ion-pumps and bio-molecular motors) or otherwise through artificial devices. In the current work the basic emphasis is over the possibility energy source instead of thermal gradient towards power delivery of a microscopic motor. In case of energy supply through external fluctuations (5–8) or otherwise non-equilibrium chemical reaction (9, 10), the state of Brownian motion remain biased in case of anisotropic as the medium, even in isothermal system. Therefore, directed motion turns up possible without the force of gravity, macroscopic mode of electric fields, or otherwise the long-range spatial gradients noted in chemicals.

In terms of device with biased Brownian motion, there is the net transport that appears through combination of diffusion as well as deterministic motion being induced through time applied externally as per electric fields. As different sized particles undergo different frictional levels and Brownian motion, there is the apt design based on external modulation that gets exploited in terms of differentiating the sizes of the particles in order to move in opposite ways (11–16). There is the scope that one can think of an apparatus that comprises of the mixture to be fed within the system from middle as well as purified fractions that get continuously removed from any of the sides. As energy is needed in order to transport over barriers of energy by thermal noise and due to
external forces that get exerted over smaller length scale, these kinds of devices are liable to appear for being operated by smaller external voltages. As against this, there are various conventional procedures, like centrifugation, electrophoresis and chromatography, that need to get turned off as well as must have newer batch of particles. Such approaches depend on motion led by long-range gradients, that have major influence over the thermal noise for the degradation of quality related to separation through diffusive broadening of bands.

Brownian Biased Motion

Brownian biased motion as in Fig. 1A can exemplify a charged particle that is liable to move an array related to the interdigitated electrodes along with spatial span of 10 mm. As voltage gets applied, respective potential energy over the particle remain approximate over an anisotropic function of sawtooth function (Fig. 1C). Though electric generator gets macroscopic device, electric field under $x$ direction remain averaged in terms of spatial span being is zero, irrespective of voltage, and thus without any need for net macroscopic force.
A fluctuation under non-equilibrium state is liable to get created by the application of switching device imposing through externally defined, yet being random in terms of modulation of voltage. Current experiments lead to the unidirectional motion under the microscopic particles that can induce through modulation of amplitude for respective anisotropic sawtooth potential (17, 18). Respective theoretical derivation specify that direction 1 of determined flow gets administered by the combination of local spatial anisotropy meant for the applied potential aspect, whereby he diffusion coefficient meant for a particle, shows specific illustrations about the way external modulation gets implied out (11–16). There are some situations, through which, particles from least different sizes can move within opposite directions, and offering the base for continuous separation. There are many technological issues, yet acts prior to the construction of the practical device. Second example for this instance is in Fig. 1B, that specify a Brownian particle moving with lattice of electric dipoles.
which are arranged from head to tail (7). Individual dipoles can be like macromolecular monomers with aggregate formation towards extended linear polymer. In such instance, there can be the particle with active site towards catalyzing hydrolysis reaction $\text{HS}_3\text{H}^+ + \text{S}^-$, that denotes S as substrate molecule. Charge over individual particle will further fluctuate, as per the state of $\text{H}^+$ or $\text{S}^-$ being bound. Potential energy related to particle with axis noted by dipole lattice gets noted as approximate illustration of sawtooth function (see Fig. 1C), yet amplitude relies on charge and thus over chemical state. As chemical reaction noted as $\text{HS}_3\text{H}^+ + \text{S}^-$ gets away from equilibrium, that holds the fluctuation over particle charge, because of reaction led by unidirectional transport. This can turn up significant under chemomechanical energy that is responsible for the conversion of biomolecular motors as well as pumps, proteins converting energy from a chemical reaction like adenosine triphosphate (ATP) hydrolysis in order to drive unidirectional transport.
Though there is the operation of biological motor that remains exactly in the simple Brownian ratchet through chemical energy to gain bias thermal noise, few instances are about the basic principles related to the respective operation. As per current experiments, enough consistent related to
the ratchet mechanism (5,19, 20), added by external oscillating (21) or the instance of fluctuating (22) electric fields are attained by driving transport through molecular ion-pump, sodium-potassium adenosine triphosphatase. Collected energy from substitutes of energy in general gets offered by ATP hydrolysis, irrespective of the average value related to the field being zero.

Transport driven by fluctuation, offers explicit mechanism in terms of coupling energy from the relevant nonequilibrium chemical reaction for local fluctuations being same as being imposed externally by driving unidirectional transport (20). Lastly, there is the scope to create microscopic motors as well as pumps implied for nonequilibrium chemical reactions as fuel. Examples are as in Fig. 1 for initiating a concrete discussion by us. Diffusion in general is about the periodic potential increase over various contexts (23), added by enzyme catalysis, that holds enzyme cycles by various intermediates in terms of carrying determined function (19); physics in solid state of transistors (24) get noted by various p-n junctions; that holds Josephson junction models (25); and further get generalized models related to computation (26). Illustrations related to the interactions are noted for offering potential rates that never critical as mechanisms for the spatial anisotropy conspiring thermal noise for permitting energy from external mode of fluctuations or nonequilibrium reaction of chemical to attain unidirectional flow. Anisotropic potentials as in Fig. 1C are ratchet potentials, within analogy towards macroscopic ratchets like car jack allowing motion under single direction through an asymmetric gears series.

Fluctuating Potential or “Flashing” Ratchet

In order to understand, the way thermal noise gets in association with externally modulated anisotropic potential, the approach can lead towards unidirectional transport, as in model (7, 27) see Fig. 2A. Particle related to damping of viscous moves with track that comprises of anisotropic potentiality added by periodically spaced wells at various positions noted as $iL$ cyclically turns, or otherwise “flashes,” on as well as ‘flashes’ off. To establish that a work can be
accomplished against external force, relevant potential profiles should get elaborated along with net force $F_{\text{ext}}$ acting specifically from right to left. In case of external force, the same is never very large, particle gets pinned close to bottom of respective wells (as at $x = 0$) as potential remains on. Without using any noise, particle is liable to move towards left added by velocity $F_{\text{ext}}/Y$ as potential remains off, that holds $Y$ as the coefficient related to viscous drag. Determined thermal noise is subject to change situation in a very dramatic way. Due to Brownian motion, there is a random walk that gets superimposed over deterministic drift, added by position related to particle noted for distribution of probability. As the potential remains off, distribution of probability drifts downhill remains with velocity $F_{\text{ext}}/Y$ and further spreads out just like Gaussian function. As the distribution (see in Fig. 2A) turns (28)

$$P(0|x; t_{\text{off}}) = \exp \left[- \frac{(x - t_{\text{off}}F_{\text{ext}}/Y)^2}{4Dt_{\text{off}}} \right] \frac{1}{\sqrt{4\pi Dt_{\text{off}}}}$$

(1)

that withstand $D$ as diffusion coefficient, as potential gets turned on all over again, particle gets trapped in well at $iL$ in case there is the difference in $L(i - 1 + QI)$ and $L(i + QI)$. Probability related to the derivations of particle in every well, $P_{iL}$, gets calculated through integrated mode of probability density (Eq. 1) among the noted limits. Due to anisotropy meant for potential, determined particle beginning at $iL$ is supposed to get trapped in well at $(i + 1)L$ instead of the well at $(i - 1)L$ in terms of smaller $F_{\text{ext}}$ added by intermediate values related to $t_{\text{off}}$. Average steps gets noted as $R$ within a cycle related to the turning of potential for a duration of $t_{\text{on}}$ in case of long term access reached by particle to the bottom of well with $(t_{\text{on}} > -yL^2/fU)$, off for a span of $t_{\text{off}}$, and again as $R = l_{00}iP$, added by average velocity ($v$) = $RL/(t_{\text{off}} + t_{\text{on}})$ (see Fig. 2B). Motion towards right appears irrespective of the push led by the macroscopic force for the particle towards left. In case of large $fU/L$, external force is needed for the flow towards identical zero, $F_{\text{stop}}$ (stopping force), is liable to evaluate appropriately (21) for $F_{\text{stop}} = (-
\( yL/t_{\text{off}})(QI -1/2). \) For \( t_{\text{off}} <(-yL/F)(QI1/2), \) just terms caused by integration of Eq. 1 along with \( i = \pm 1 \) offering tribute towards velocity. Under such regime, velocities scale added by \( D/L \) and relevant times added by \( L^2/D. \)

Mechanism as noted in Fig. 2 works irrespective of diffusion as well as thermal noise, yet due to diffusion. As potential gets turned off, particle diffuses remained symmetrical. It is after this, that as anisotropic potential get turned on, and remain more supportive for particle to feel necessary force towards right rather than left. Therefore, net motion appears towards right, even though there is the presence of smaller homogeneous force towards left. Respective energy is liable to drive transport, yet never comes from thermal noise, offered as potential gets turned on. The attained energy is subject to get assessed by means of integrating over the product of \( U_{\text{on}}(x) \) and further the probability density \( P(0 \leq x; t_{\text{off}}). \) As the potential is long enough to permit particle in terms of reaching bottom of a well, there remains no energy to get returned as potential remains turned off. Output energy noted in every cycle contains steps \( R \) that is multiplied by gained energy/step \( F_{\text{ext}}L. \) Difference in such energies remains dissipated in terms of heat that results from viscous dragging particle along with solvent. In reference to a simple model noted in Fig. 2, the efficiency of thermodynamic remains lesser than 5% (29). There are other features being biased to the Brownian motion turning it as more promising in terms of the construction related to the microscopic motors. In reference to a spatial span of 10 mm, velocities for a 0.3 mm/s is possible to gain through a 2-mm particle added by \( t_{\text{off}} \) s in terms of aqueous solution (see Fig. 2B, the solid line). Such motor can act in contrast to a large force like 0.05 pN, and thereby can easily overcome gravity, that stands for 2-mm particle along with a density assessed as 1.05 g/cm\(^3\) in water at an assessed 0.004 pN. Contents of larger particles, still never gets over gravity as well as drift towards left as \( t_{\text{off}} \) gets larger (Fig. 2B, as in dashed line). Determined velocity relies over non-monotonically structured frequency modulation (see Fig. 2B) and gets comprehended as competing demands for the particle to get the capability for
diffusing least mode of short distance $aL$, yet not for longer distance $(1 \ 2 \ a)L$ whereas potential remains off. Non-monotonic behavior permits the possibility of attaining device tuning towards frequency features for respective particle. Such tuning can remain helpful in the process of implementing the act of separating particles, as per size, yet the bandwidth of response will remain relatively wide. There is the possibility that a person can exploit dependence, yet through the process of imposing external force to move some particles toward right and others towards left. Simplest way to exemplify this has been noted in Fig. 2C that aims in tilting an apparatus like the one noted in Fig. 1A. This is because particles experience net gravitational force represented as $F_{\text{gravisin}}(u)$, denoting $u$ as angle relative to horizontal surface. Smaller particles are supposed to feel a very minimal force caused by gravity as well as larger account of Brownian motion that can stand biased through ratchet towards the cause of motion being uphill towards right. Larger particles comprise lesser Brownian motion and as such feel greater force caused by gravity as well as move downhill towards left. Under such condition, particles mixture containing different sizes can get introduced within middle as well as purified fractions that are collected in a continuous format over both the ends. Due to close spacing in electrodes, very least voltage remains necessary for the attainment of sufficient larger barrier of energy.

As noted in Fig. 2C, the proceeding does not stand apt for smaller particles as gravity remains insufficiently strong. Still, there are other kinds of similar strategies that are liable to get adopted, along with the application of constant electric field in terms of homogeneous force (16). Thus, with more complicated pulse protocol rather than simple square wave, there are particles in various sizes that are liable to get induced in terms of moving under opposite directions without homogeneous element of long-range force (12, 13, 15). Through the process of exploiting varied scaling meant for biased Brownian motion as well as motion induced through deterministic kind of gravitational as well as electric forces, proceedings for continuous separation of determined particles from macromolecular (1028 m) to
the mesoscopic (1025 m) size remain possible.
Core principles related to motion get induced through fluctuation of potential aspects that are recently tested in terms of simple systems of the model. Rousselet et al. (17) implied time-dependent ratchet potential towards colloidal particles by the application of inter-digitated electrodes of “Christmas tree”, which are deposited over glass slide by means of photolithography. Cyclically is subject to turn potential on and off till net flow is met.
Irrespective of complexity in dealing with suspension over various interacting particles, relevant data remain agreed for semi-quantitative predictions over simple theory. Same kind of effect get demonstrated through Faucheux et al. (18), who implied single colloidal particle under optical trap which gets modulated towards the process of generating sawtooth potentiality. This is a kind of setup that holds the advantage of a single particle, thus considering the process of eliminating inter-particle hydrodynamic interactions.
Modulation of potential demands for work, stands without any question for devices as “perpetual motion machines.” Most surprising aspect about the flow gets induced without macroscopic force, whereby all he forces comprises local and act over a span of order meant for a single period of determined potential. However, motion persists in an indefinite way, for various span of time. As against this, conventional approaches related to particle separation like chromatography, centrifugation, or electrophoresis depend over macroscopic gradients and is subject to get operated as “batch” separators.

Fluctuating Force, or “Rocking” Ratchet
In respectively selected mechanism of Fig. 2, it has been derived and showed that the spatial average noted in case of force remains independent of any time span, and the same is temporal modulation in case of changes that are for the shape meant for potential entity on local basis.
Another researched approach for the purpose of driving flow over ratchet potential remain inclusive of determined application as in fluctuating net force (6, 11, 14, 23, 30, 31). This is the notable approach that remain visualized in the rocking form for
the sawtooth potential as depicted in Fig. 1C on a back and forth way among limits $\pm F_{\text{max}}$ (Fig. 3). If $\Delta U/[(1 - \alpha)L] < |F_{\text{max}}| < \Delta U/(\alpha L)$, decrease in potential energy monotonically is meant toward left as respective force gets represented as $-F_{\text{max}}$, yet as force remains noted as $+F_{\text{max}}$, there are minima which is noted as trap for the particle since it moves towards right in response towards the applied force (see Fig. 3A). Therefore, this can be noted even without thermal noise, there is a slow oscillation noted among the force $\pm F_{\text{max}}$ as net flow is meant towards left.

Instance of fast oscillation never lead to net flow as particle does not comprises of any time towards movement of a period $L$ prior to force that stands reverse to the sign. Application of fluctuating/oscillating force remains analogous towards standard way of driving electrical rectifier, otherwise macroscopic mechanical ratchet like those of car jack or ratchetting screwdriver.

Presence of thermal noise permits sub-threshold fluctuating force $|F_{\text{max}}| < \Delta U/[(1 - \alpha)L]$ to cause flow (6). For slow, zero-average square wave modulation related to force among $\pm F_{\text{max}}$, average rate that gets calculated through the application of analytic formula as has been noted by Magnasco (6). As derived in Fig. 3B, average velocity gets plotted in the function of $F_{\text{max}}$ that gets dashed lines that gets marked for the location related to the threshold forces $\Delta U/[(1 - \alpha)L]$ and $\Delta U/(\alpha L)$. It is in Fig. 3C, that the average velocity gets plotted in the form of function meant for thermal noise strength denoted by $k_B T$ (where $k_B$ that gets Boltzmann’s constant as well as $T$ being the temperature) for sub-threshold that remains applicable force $(F_{\text{max}} = 0.4 \text{ pN})$. We have seen that increasing noise can in reality increase flow that has been induced through the process of fluctuating force, that again suggests some technological applications, which are very useful towards electronically added noise meant for the system.
For the forces that are closer to optimum (\(F_{\text{max}} = 1.5\) pN in Fig. 3B), velocity on the other hand, decreases almost in a very monotonically determined way, added by increasing noise.

**More-General Approach**

By considering a more general kind of approach towards investigation of fluctuation-driven transport which are comprised of solving diffusion equation, we can note-

\[
\frac{\partial P(x,t)}{\partial t} = - \frac{\partial}{\partial x} \left[ \frac{U''(x)}{\gamma} P(x,t) \right] + D \frac{\partial^2 P(x,t)}{\partial x^2}
\]

(2)

At equilibrium, density of the probability as noted by Boltzmann distribution is

\[
P(x) \propto \exp \left( -\frac{U}{k_B T} \right).
\]

Any modulation related to the external temporal of \(U\), is noted in case of accomplished aspects noted periodically or otherwise randomly marked in time, and further demands for energy input as well as is liable to get derived for the system that is away from equilibrium, disturbing the approach through Boltzmann distribution.

Time dependence noted for the \(U\) in terms of fluctuating potential ratchet gets noted as \(U(x, t) = f(t) U_{\text{saw}}(x)\), and further for fluctuating force ratchet, noted as

\[
U(x, t) = U_{\text{saw}}(x) + x f(t).
\]

It is through Equation 2 that we can resolve for \(P(x, t)\) for any kind of explicit time in accordance to \(f(t)\) that is noted for being apt (typically under periodic formulation) that is subject to boundary conditions, along with the result that is implied for the calculation of average velocity. However, this turns out to be noted under various cases, it remains comparatively simpler to resolve Eq. 2 as \(f(t)\) gets modelled in terms of position-independent stochastic variable (31). Such kind of instance should not get confused with an equilibrium fluctuation.

At equilibrium, probability is subject to undergo transition from a state to another, as per energy difference noted among states as has been marked by Boltzmann relation (or the detailed balance), along with energy difference meant for a ratchet that is potentially clear and is in accordance to respective position. There is an external modulation that is referred in case of random or otherwise non-random
status, which is not for the purpose of conforming detailed balance as well as is not liable to model equilibrium fluctuations. As against this kind of situation, motion that gets driven through the forces like gravity/macroscopic electric fields, in case the motion direction gets determined through the force sign, direction further gets flow which is induced through zero-average modulation related to a potential/force relying on details related to the way modulation gets carried out. In a recent approach, there are many schemes gets proposed and further permits for flow by the reversal to appear under function of the modulation frequency, added by different reversal frequencies meant particles added by different diffusion coefficients (13–18).

**Chemically Driven Transport**

By considering one-dimensional motion in a charged particle added by a periodic lattice related to dipoles that are arranged from head to tail (see Fig. 1B), and allows interaction among lattice and particle being purely electrostatic (7). Profile of potential energy further comprises of periodic series related to the minima (wells) as well as maxima (barriers). In a simple way, this is a profile that is subject to represent function of sawtooth (see Fig. 1C). Due to the thermal noise, particle is subject to undergo Brownian motion. On an occasional basis, the same holds enough energy in order to pass over 1 out of 2 barriers that are surrounding respective well, where it begins as well as move towards the well over the right/left. Irrespective of anisotropy, which stands without any supply of energy, there are two probabilities that stand equal to each other.

At this point just imagine the respective particle being catalyzed by chemical reaction noted as \( \text{HS} \overset{\cdot}{\rightarrow} \text{H}^+ + \text{S} \). Since, the product molecules \( \text{H}^+ \) and \( \text{S}^- \) get charged, amplitude related to the interaction potential among particle as well as the dipole lattice relies over the instance that can be \( \text{H}^+ \) or \( \text{S}^- \) can get bound toward the particle, that consequently shows a coupling among chemical reaction added by diffusion of particle added by dipole lattice. Due to the charge over \( \text{H}^+ \) and \( \text{S}^- \), local concentrations are noted to remain different under various function related to
the position over the dipole lattice axis (hydrogen ion concentration [H+] being larger near negative end noted in context of the dipole irrespective of being close to positive end, added by the opposite instances that is true for [S-]). The radii noted over ions [H+] and S- get marked for being very small as against radius of particle, so that their local concentrations stand equilibrated in a much quicker way, and further is subject to lead towards [S-] = [S-]_{bulk} \exp[-U(x)/k_BT] and [H+] = [H+]_{bulk} \exp[+U(x)/k_BT], where subscript “bulk” stands to represent concentration being far from surface of dipole lattice. In context of the determined mechanism as has been declared and shown in Fig. 4A, k_{21}, k_{23}, and k_{31} are subject to get identified for the first-order rate remaining absolutely constant and never relying on position added by the dipole, as well as k_{12} = k_{12}[SH], k_{13} = k_{13}[H^+], and k_{32} = k_{32}[S^-] being noted for being pseudo–first-order rate which stands coefficiently into concentrations related to the reactants having incorporated as per the formulations. As [H+] and [S-] rely over position x added by the dipole lattice, rate of the coefficients k_{13} and k_{32} further relying over position.
In case the chemical reaction stands equilibrium, there is the possibility of direct transition as has been noted from uncharged state $i = 3$ towards charged state $i = 2$ that stands more likely to remain closer to the positive end of dipole, that withstand $[S^-]$ being relatively high, rather than being nearer to the negative end of respective dipole, that withhold $[S^-]$ being relatively low. In the same way, there is room for direct transition attained from charged state $i = 1$ towards the uncharged state $i = 3$ that remains more likely get closer to negative end of respective dipole, that withhold $[H^+]$ as a relatively higher than being nearer to the positive end in context of the respective dipole. It is here that $[H^+]$ remains relatively low. Net effect gets transitions from charged to uncharged state and relevantly remains more likely to be closer to the negative end.
of respective dipole, added by the transitions as has been collected from uncharged to charged state, which are subject to remain more likely closer to positive end of respective dipole. As per Boltzmann distribution, under such circumstances, (and in a phase where there is absence of external force), probability density related to the particle gets distributed in all kinds of places (Fig. 4B, dashed line), added by average velocity noted for the particle being zero. In case of chemical reaction being away from determined equilibrium, there is the room for creating relation among the position of selected particle added by the transition probabilities that are not necessarily holding the particles (Fig. 4B, solid line). Under extreme case that withstand \([H^+] = [S^-] = 0\), shows direct mode of transitions from state 1 to 3 added by the development from state 3 to 2 that are not subject to appear in any situation. None of such rate coefficients are meant for remaining transitions that rely over particle’s position and thus the probability meant for the transition remain charged towards uncharged state which is independent towards the position added by dipole lattice axis, as in the case of probability for the matter of transition from uncharged to charged state. This is a situation that stands similar to illustrated fluctuating potential ratchet (see Fig. 2), as well as same as mentioned above. This gets directed motion. Therefore, we have rudimentary motor that is subject to get driven through chemical reaction. Mechanism as has been noted herewith in Fig. 4A, specifically notes the tremendous mode of oversimplification in the form of a description related to the real molecular motor. Necessary interaction between motor as well as dipole lattice and relevantly noted effect over the catalyzed reaction get assumed to remain purely electrostatic. Consequently, this ends up with the resulting span of potential duration that gets simplified in a grossly manner. Nevertheless, in addition of reasonable values related to the constant rates as well as other parameters, determined motor moves in a much better way (see Fig. 4C), added by a maximal velocity related to various micrometers/second. Stoichiometry remains poor: there is the need for more than 3 HS molecules at an average
towards the process of causing single step (that is for the displacement made through period $L$), and noted to be lesser than 1 pN of the respectively implied force stops meant for the motion. The only thing that the simplified motor lacks is a real biomolecular motor that is subject to remain offered on a certain level: more in terms of complex interaction noted among track and motor, offered through conformational flexibility, added and further regulated in a better way for coupling among chemical as well as mechanical events, that are liable to get offered by allosteric interaction as can be specifically noted among track and motor.

**Perspective and Outlook**

Noise remains as an unavoidable instance for any kind of system under thermal contact added by its surroundings. In case of technological devices, this remains as a typical way to incorporate mechanisms in context of reducing noise towards an absolute minimal range. Alternative approach from this remains effective in attempting approached for harnessing noise for necessary purposes. This can be exemplified by the involvement of signal detection through threshold detectors (32). On a typical note, these devices get designed in a way that the system gets totally isolated from any kind of noise, as well as the threshold being smallest ever possible. However, these are the goals that are hard and expensive. Rather, it can remain possible to operate respective system added by a threshold that can be larger than signal for the assessment and application added by noise in order to offer boost for permitting signal towards the detection level above noise. Phenomenon over the noise-enhanced status and the signal-to-noise kind of ratio gets termed as stochastic resonance and the same further holds wide variations in the nonlinear systems (32, 33). In the same way, transport driven by fluctuation implies noise towards the accomplishment of mass transport that stand without any sort of macroscopic force or gradient. There are three ingredients marked as important in this context. These are:

(i) thermal noise causing Brownian motion;

(ii) anisotropy from the medium structure where the particle diffuses; and
(iii) Energy supplied by external variation and chemical reaction being far from equilibrium.
Fig. 4. Transport driven by a chemical reaction. (A) Schematic illustration of how the potential energy profile of a Brownian particle that catalyzes a reaction \( S^- + H^+ \leftrightarrow S^- + H^+ \) changes depending on its chemical state, even in a constant electric potential due to a dipole array as shown in Fig. 1B. (B) Probability of the particle being uncharged \( P_3(x)/\Sigma P_i(x) \) as a function of position when the chemical reaction \( S^- + H^+ \leftrightarrow S^- + H^+ \) is at equilibrium (dashed curve) and far from equilibrium (solid curve). For simplicity, we treat the case that the particle bears a charge of \(-1\) and that the interaction potential between the particle and dipole track (Fig. 1B) is purely electrostatic. Because \( S^- \) and \( H^+ \) are charged, their local concentrations depend on the local potential according to \( [S^-] = [S^-]_{\text{bulk}} \exp[-U(x)/k_BT] \) and \( [H^+] = [H^+]_{\text{bulk}} \exp[+U(x)/k_BT] \). The rate constants used were \( k_{21} = 10^5 \text{ s}^{-1} \), \( k_{22} = 10^6 \text{ s}^{-1} \), \( k_{33} = 10^6 \text{ s}^{-1} \), and \( k_{34} = 100 \) s\(^{-1}\), \( k_{35} = 100 \) s\(^{-1}\), and \( k_{36} = 100 \) s\(^{-1}\), all in inverse millisecond, and the concentrations were \( [S^-]_{\text{bulk}} = 4 \text{ M} \), \( [H^+]_{\text{bulk}} = 2 \text{ M} \), and \( [S^-]_{\text{bulk}} = 2 \text{ M} \) for the equilibrium case, and \( [S^-]_{\text{bulk}} = 20 \text{ M} \), \( [H^+]_{\text{bulk}} = 0.05 \text{ M} \), and \( [S^-]_{\text{bulk}} = 0.05 \text{ M} \) for the far from equilibrium case, all in millimolar.

The amplitude of the potential \( \Delta U \) was \( 10^{-20} \text{ J} \). (C) Average velocity as a function of the \( \Delta G \) of the chemical reaction using the rate constants and field amplitude as in (B). This result can be calculated in general by using reaction-diffusion equations to describe the combined physical motion and chemical reaction of a catalytic Brownian particle as described elsewhere (9, 10). Here, \( k_{22} \) and \( k_{33} \) were taken to be large so that state 2 could be treated as a steady-state intermediate. Then, there are effectively only two states, "off" and "on," as in Fig. 2, with the effective time constants \( \tau_{\text{off}} = [S^-]_{\text{bulk}} \exp[-U(x)/k_BT] + 100 \) s\(^{-1}\) and \( \tau_{\text{on}} = [S^-]_{\text{bulk}} \exp[+U(x)/k_BT] + 100 \) s\(^{-1}\), as described in (9). The value of \( \Delta G = -RT \ln([S^-]/([S^-]_{\text{bulk}} + [H^+]_{\text{bulk}})) \) (\( R \) is the universal gas constant) was varied by varying \( [S^-]_{\text{bulk}} \) with constant \( [S^-]_{\text{bulk}} = [H^+]_{\text{bulk}} = 1 \). The period \( L \) was taken to be \( 10^{-9} \text{ m} \), and the viscosity at the interface was taken to be greater than in bulk water \( (\eta = 0.006 \text{ Pa s}) \), resulting in \( \gamma = 6\pi r \approx 2 \times 10^{-6} \text{ N s/m} \) for a particle with a Stokes radius of \( r = 10^{-9} \text{ m} \) and a diffusion coefficient \( D = 2 \times 10^{-9} \text{ m}^2/\text{s} \). The inset shows that there is a linear relation between flow and \( \Delta G \) close to equilibrium. The nonmonotonic dependence on \( \Delta G \) arises because \( \Delta G \) is changed by varying the chemical concentrations, which also varies the time scales.
In general, the approach gets overlooked in context of the noise-assisted proceeding that is liable to incorporate determined characteristics. These are analogous towards the chemical kinetics (34). The state of transitions added by chemical pathway remain illustrated in reference to the constant rate that is subject to reflect for the probability that is meant for the thermal noise, offering sufficient energy in order to surmount barrier of energy which is subject to separate chemical states. Necessary experiments related to the ion pumps showed energy from the state of externally imposed electric oscillations (21) along with fluctuations (22). These are subject to get substituted for energy that is noted from ATP’s hydrolysis towards power of the uphill transport of ions. The very possible mechanism noted in this aspect is about the biased thermal activated approaches in the pathway of reaction — a Brownian ratchet mechanism (5, 19). As summarised by Lauger “Ion pumps do not function by a ‘power-stroke’ mechanism; instead, pump operation involves transitions between molecular states, each one of which is very close to thermal equilibrium with respect to its internal degrees of freedom, even at large overall driving force” (35).

However, it is still to get clear, if the molecular motors like muscle (myosin) or otherwise the kinesin move through the application of ATP-driven power stroke, which is recognised for being a process under visco-elastic relaxation. It is here that the protein starts from nonequilibrium conformation followed by phosphate that gets released as well as never in demand of thermal activation, or if energy gets noted from ATP’s hydrolysis implied towards the bias thermal activated proceedings. A very current research work on the Brownian ratchets relevantly showed thermally activated approach as a mechanism that withstand non inconsistent status with a sort of approach whereby the protein moves distance of 10 nm within a single step. This is further subject to generate force over various pico-newtons. This is a query that aims to get resolved by the application of recently developed techniques in terms of studying molecular motors at single molecular level (36).

Incorporation noted in context of thermal motion stands as an important feature in the trend of designing microscopic
machines. This stands equivalent to the process of adopting design principles that gets borrowed from the chemistry instead of classical macroscopic physics. A very notable feature is about the fundamentally established stochastic nature related to the noise-assisted transition that gets “activated” in order to give rise to the process that is very much rival to the purely considered and deterministic approach, especially in the predictability mode of understanding specific outcomes. This is a kind of possibility that gets analysed and further discussed through Bennet under the thermodynamic comparison made over computers that are based on Brownian versus ballistic principles (37). As per recent research works, coupling many kinds of particles within a predetermined modulated ratchet stands with the potentiality that offers increase of extraordinarily rich kind of behaviour as well as thermodynamic efficiencies to a level of 50% (38). Application of noise in this particular way under technologically applied aspect remains in its infancy, and is still very far from the state of having a clearer perception for the futuristic status. On the other hand, much active mode of researches is noted in the field of noise enhanced magnetic sensing (39) as well as electromagnetic communication (40). Current research works are subject to remain fluctuating and the transport leads towards optimism of gaining same kind of principles that can be implied towards the process of designing microscopic pumps as well as motors. This refers to machines that are typically based on deterministic approaches and are inclusive of cogs, springs and levers — from stochastic kind of elements which are modelled over the principles of reactions noted in chemicals and noise-assisted approaches. These kinds of derivations are subject to remain consistent along with behavior of the molecules that comprises of enzymes, and are subject to pave way towards the construction of truly identified molecular motors as well as pumps.

References


