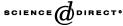


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Asymmetric confinement in a doubly modulated bistable device

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Abstract

A Brownian particle hopping in a symmetric double-well potential may be statistically confined into a single well by the simultaneous action of two periodic input signals, one tilting the minima, the other one modulating the barrier height. Such a basic mechanism for asymmetric confinement can be conveniently maximized by tuning the input signal parameters (frequencies, phase lag, amplitudes), thus leading to a resonant localization of the particle in a target potential well.

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A Brownian particle bound by a bistable potential diffuses symmetrically between the potential minima; this is the case of Kramers' dynamics [1], where the particle is activated by thermal fluctuations, as well as of stochastic resonance (SR) [2,3], where the particle escape over the potential barrier is controlled by the interplay of thermal fluctuations and external periodic drive(s). In both cases, the time-averaged particle distribution density peaks symmetrically in correspondence with the potential minima; particle localization into one well is customarily achieved by applying an external static bias that breaches the symmetry of the system [4].

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In a number of applications experimenters are interested in confining the diffusing particle around one stable configuration and then manipulating it by means of various techniques; recent examples include magnetic flux microscopy [6], laser traps [5], quantum device design [7], to mention but a few. However, in most circumstances adding an external bias to the system at hand is inconvenient; hence, the need for an alternate approach to the confinement problem.

In the present paper confinement in a noisy bistable device is achieved without apparent symmetry breaking. A Brownian particle driven by a white, zero-mean Gaussian noise (mimicking thermal fluctuations) and, possibly, by a sinusoidal force with angular frequency Ω_1 , may be localized into one state by modulating the potential barrier separating the two degenerate states. To this purpose one can input a sinusoidal (multiplicative) control signal with frequency Ω_2 and appropriate phaselag. The corresponding steady distribution develops one prominent peak, whose relative magnitude hits a maximum for optimal values of the input parameters; in whose degenerate state the particle gets trapped in, depending on the switch-on phase of the modulating signal.

The key mechanism underlying the phenomenon of asymmetric confinement is well illustrated by the simplified case of an overdamped Brownian particle of coordinate x(t) diffusing in a quartic double-well potential $V(x) = -ax^2/2 + bx^4/4$, with a,b>0, subjected to a zero-mean Gaussian noise $\xi(t)$ and two low-amplitude rectangular signals $\varepsilon_i(t) = \varepsilon_i \operatorname{sgn}[\cos(\Omega_i t + \phi_i)]$, with i=1,2 and period $T_i = 2\pi/\Omega_i$, namely

$$\dot{x} = a[1 + \varepsilon_2(t)]x - bx^3 + ax_0\varepsilon_1(t) + \xi(t) \tag{1}$$

with $\langle \xi(t)\xi(0)\rangle = 2D\delta(t)$. Here, the additive signal $\varepsilon_1(t)$ tilts the potential sidewise, whereas the control signal $\varepsilon_2(t)$ sets the symmetric barrier separating the degenerate unperturbed minima $\pm x_0 = \pm \sqrt{a/b}$, to a high/low height $\Delta V_{\pm} = \Delta V_0 (1 \pm \varepsilon_2)^2$, with $\Delta V_0 = a^2/4b$.

The steady (time-averaged) distribution density P(x) of the stochastic process (1) has been computed by standard numerical simulation. In Fig. 1a our numerical results for $\Omega_1 = \Omega_2$ and $\phi_1 = \phi_2 = 0$ exhibit a marked asymmetry, corresponding to a stochastic localization of the particle to the left, i.e., in the negative potential well. The qualitative interpretation of such occurrence is straightforward: As long as the driving force $\varepsilon_1(t)$ points to the right, the barrier is set to its larger value ΔV_+ , so that the Brownian particle takes a relatively long time to jump into the more stable well to the right (from where it can hardly escape); vice versa, as the additive force reverses sign, the barrier switches to its lower value ΔV_- , thus speeding up the right-to-left escape process. As a result, the spatial distribution density P(x) tends to accumulate around $-x_0$. Of course, shifting the relative phase $\phi_2 - \phi_1$ by π is equivalent to changing $x \to -x$ and thus reversing asymmetry, as shown in Fig. 1a.

The *gating* mechanism [8] invoked here is expected to become increasingly efficient as D is lowered below ΔV_0 . In Fig. 1b the subtracted asymmetry factor $\sigma \equiv P_-/P_+ - 1$, with $P_\pm \equiv \langle \int_0^\infty P(\pm x,t) \, \mathrm{d}x \rangle_t$ and $\langle \cdots \rangle_t$ denoting the stationary time average taken over one forcing cycle, diverges exponentially for $D \to 0$ and tends to zero (no confinement) according to a power law for $D \to \infty$.

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