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Nucleation of Breathers via Stochastic Resonance in Nonlinear Lattices

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Intrinsic localized modes, often referred to as discrete breathers, have been experimentally observed in a wide variety of different media, ranging from optical waveguides and photorefractive crystals to micromechanical cantilever arrays and Josephson junctions, as well as in Bose-Einstein condensates and layered antiferromagnets, among many others [1, 2].

In the present work, having in mind realistic physical systems, we will focus on the nucleation of such breathers in a prototypical model system in which friction and ambient noise are also present. This will lead us to the consideration of stochastic resonance (SR), the counterintuitive phenomenon by which an appropriate dose of noise, instead of degradation, produces an enhancement of sensitivity of a nonlinear system to external forcing [4]. In spatially extended systems, SR has been shown for bistable [3] or excitable media [4], usually associated with pattern formation [2], see e.g. the review of [4].

Our prototypical nonlinear model will consist of a quartic potential (the so-called hard $\phi^4$ lattice [8]) with the following equation of motion for each oscillator $x_n$ ($n = 1, \ldots, N$) with mass $m$

$$m\ddot{x}_n = -U'(x_n) + k(x_{n+1} + x_{n-1} - 2x_n) - \alpha\dot{x}_n + \xi_n + F_n(t),$$

where the overdot and the prime denote time and space derivative, respectively; $k$ is the coupling parameter between oscillators; $\alpha$ the damping constant; $F_n(t)$ denotes external driving; and $\xi_n$ is a Gaussian white noise with zero mean and autocorrelation $\langle \xi_n(t)\xi_m(t') \rangle = 2D\delta_{nm}\delta(t - t')$. The noise strength parameter $D$ obeys the fluctuation-dissipation relation $k_BT = D/\alpha$, where $k_B$ is the Boltzmann constant and $T$ the ambient temperature. Thus, $D$ is an indicator of the level of noise associated with thermal fluctuations.

The on-site potential is given by $U(x) = ax^2/2 + bx^4/4$ with $a, b > 0$. This is a monostable nonlinear potential which confers interesting properties to the lattice. The fact that is monostable implies that the noiseless lattice has a single stable steady state, allowing us to focus on the behavior of homoclinic orbits, rather than kink-like heteroclinic orbits, like in the bistable $\phi^4$ case ($a < 0$). This is one way in which our work differs from the standard bistable models of SR, or the interesting recent work of [4], which considers noise-induced transitions between steady states in very short Fermi-Pasta-Ulam (FPU) type, boundary-driven chains. Moreover, this model possesses a phonon band which can be easily determined upon linearization of (1) as $\omega_{ph} \in (\sqrt{U''(0)/m}, \sqrt{U''(0) + 4k}/m)$ [1]. Thus, by exciting breathers with a frequency larger than the maximum frequency of the phonon spectrum, $\omega_{max} = \sqrt{(a + 4k)/m}$, these localized modes are guaranteed not to interact with the phonons, avoiding effects like radiation resonances which slowly dissipate away the energy of discrete breathers [10].

Indeed, the associated Hamiltonian system of this hard model (i.e., Eq. (1) without damping and noise) exhibits exponentially localized in space and periodic in time high (i.e., higher than $\omega_{max}$) frequency excitations. An example is the dynamically stable Sievers-Takeno (ST) [11] site-centered mode. As shown in Fig. 1, this mode is staggered, i.e., the neighboring sites oscillate out of phase. Hence, these breathers will necessitate that we impose staggered periodic driving in order to sustain them in the presence of dissipation. For this reason, we shall consider the following AC driving force

$$F_n(t) = (-1)^nF_0\sin(\Omega t).$$

Its effect on a deterministic FPU lattice has been studied in Refs. [12, 13]. Furthermore, such staggered driving is straightforward to apply to driven nonlinear electrical lattices [24]. Evidently, the driving frequency $\Omega$ must be
chosen with the same value as the breather frequency we are interested to excite.

The equations \( (1) \) are supplemented with (periodic) boundary conditions \( x_0 = x_N \) and \( x_{N+1} = x_1 \). Generally, \( \phi^4 \) models has been commonly used to describe a wide range of phenomena from elementary particle collisions and cosmological domain walls \([14]\) to the behavior of an order parameter near the condensation point of a droplet in nucleation theory and phase transition phenomena \([12]\). They also constitute a prototypical nonlinear model in statistical field theory \([16]\).

For the sake of a dimensionless description, we can scale all lengths and times by the characteristic length \( \lambda = (a/b)^{1/2} \) and time \( \tau = (m/a)^{1/2} \), i.e. \( \tilde{x}_n = x_n/\lambda \), \( \tilde{t} = t/\tau \), which implies \( \tilde{k} = k/a \), \( \tilde{\alpha} = \alpha/(am)^{1/2} \), \( \tilde{D} = bD/(a^3m)^{1/2} \), and \( \tilde{F} = F_0/(a^3)^{1/2} \). In the following we will omit the tilde symbols for simplicity. The dimensionless form of the equations of motion \( (1) \) then reads

\[
\begin{align*}
\ddot{x}_n &= -x_n - x_n^3 + k(x_{n+1} + x_{n-1} - 2x_n) - \alpha \dot{x}_n \\
&\quad + \xi_n + (-1)^n F_0 \sin(\Omega t). \quad (3)
\end{align*}
\]

Let us discuss, for the moment, the deterministic behavior of \( (3) \) (i.e. without noise, \( D = 0 \)). As mentioned above, the staggering factor \( (-1)^n \) in \( (2) \) is important in order to sustain the breathers in the presence of dissipation. When that factor is absent, the ST breather shown in Fig. 1 is always observed to die out, regardless of the driving strength. However, in addition to this staggering factor, the driving amplitude \( F_0 \) must be large enough so that the energy supplied by the driving force is able to compensate the energy which is been dissipated by the friction force. Breathers in the dissipative deterministic lattice can be calculated using a method similar to the developed in \([18]\). An analysis of those breathers shows that, for \( k = 1 \) and \( \alpha = 0.1 \) and a breather frequency of \( \omega = \Omega = 3 \), there is a threshold at \( F_{\text{th}} = 0.6092 \).

When the driving amplitude is below this threshold (subthreshold amplitude), the dissipation drains away gradually the system’s energy and breather modes cannot be supported. In the following, unless explicitly stated, we will assume \( k = 1 \), \( \alpha = 0.1 \), and \( \Omega = 3 \), which implies \( \omega_{\text{max}} = \sqrt{3} < \Omega \).

Having summarized the results of the deterministic case, let us now turn to the analysis of the effect of thermal fluctuations and how they modify this picture. Starting with the suprathreshold case \( (F_0 > F_{\text{th}}) \), we would expect that the addition of noise provokes the spontaneous formation of breathers with the frequency dictated by the external driving, even if the system starts from an uniform configuration. This is indeed what is observed, as shown in Fig. 2 where a typical realization of the oscillators’ trajectories has been plotted. The frequencies and amplitudes of the observed noise-induced breathers are very similar to the deterministic ST breather depicted in Fig. 1. The ST breather has the smallest size and the lowest energy of all possible collective modes at the frequency of the driver, thus being the most probable breather to be induced by noise. However, unlike the deterministic case, the breathers are not permanent, and the same random force which has generated them is able to destroy them after a while.

In the subthreshold case the driving force is not able by itself to sustain the breathers. Remarkably, however, the simulations show that these breathers are still pro-
The oscillations of a Brownian particle in a bistable potential subject to a suprathreshold driving force will result in a larger coefficient $q$ for the formation of breather-like excitations in realistic nonlinear lattices where fluctuations are present. This scenario should offer a generic mechanism for the formation of breather-like excitations in realistic nonlinear lattices where fluctuations are present. Nevertheless, let us note that a non-monotonic behavior is also obtained when we inhibit breather formation by canceling the interaction between the oscillators. The dotted line in Fig. 4 shows this feature for a system with $k = 0$. This is a well-known phenomenon for any single-oscillator system subject to a nonlinear monostable potential, both in the underdamped or overdamped regime. In the former, the peak is produced by a matching between the driving frequency and the intrinsic frequency associated with the most probable excitation energy, which is a monotonic function of the noise strength $\alpha$. In fact, a simple classical mechanics analysis of the undriven Hamiltonian system $\langle \alpha, D, F_0 = 0 \rangle$ with $k = 0$ shows that a periodic solution with frequency $\omega = 3$ corresponds to an energy per particle value of $E/N = 36$. Under thermal equilibrium ($F_0 = 0$), we need to raise the temperature to a value such that the noise strength is $D = 1.67$ in order to obtain an average energy per particle of the same value. It can be seen in Fig. 4 that this value of $D$ is in good agreement with the position of the maximum. A similar
argue that also holds when we switch on the interaction between the oscillators, though now collective excitations associated with lower energies are allowed, resulting in larger amplitudes with a peak at a lower value of $D$. The total energy associated with the breather presented in Fig. 1 is $E = 30$. If we consider that roughly only $l = 5$ oscillators are needed to form the ST breather, an average energy per particle of $E/N = 6$ would be necessary in order to optimize breather formation. This value is obtained at thermal equilibrium when $D = 0.7$, which is a reasonable estimate of the peak position observed in Fig. 1. A better estimation, namely a peak at $D = 0.47$, is obtained if we choose $l = 7$ oscillators. The appropriate value of $l$ is determined by the correlation length, as discussed below.

For an arbitrarily small driving amplitude $F_0$, linear response theory predicts

$$\langle x_1(t) \rangle_{eq} = \int_0^\infty ds \chi(s) f(t-s),$$

where $f(t) = F_0 \sin(\Omega t)$ and $\chi(t)$ is the response function. This function can be expressed in terms of equilibrium time correlation functions,

$$\chi(t) = -\frac{\alpha}{D} \frac{d}{dt} \langle x_1(t) M(0) \rangle_{eq},$$

where $\langle \ldots \rangle_{eq}$ denotes equilibrium averages in the absence of driving and $M(t) = \sum_{n=1}^N (-1)^n x_n(t)$ is part of the perturbing Hamiltonian $-Mf(t)$ associated with the external driving. The calculation of the Fourier coefficient of $\chi$, together with the definitions $\chi_r = \int_0^\infty \chi(t) \cos(\Omega t)$ and $\chi_i = \int_0^\infty \chi(t) \sin(\Omega t)$, yields the following spectral amplification $\eta = |q|^2/F_0^2$

$$\eta = (\chi(0) - \chi_1^2\Omega^2 + (\chi_i\Omega)^2).$$

Fig. 5 shows the linear response results obtained from simulations at thermal equilibrium. It is seen that a driving amplitude of $F_0 = 0.05$ is small enough to be within linear response theory. Due to the presence of noise and dissipation, the correlation between two separated oscillators decreases rapidly as their separation is increased. In fact, Fig. 5 shows that a good approximation is obtained if the time correlation functions $\langle x_1(t)x_n(0) \rangle_{eq}$ corresponding to oscillators separated by more than 2 sites $(|n-1| > 2)$ are neglected in Eq. (6). This approximation is consistent with the above energy matching argument with $l = 5$, and the dominant dynamical role of ST breathers, leading to the peak estimation at $D = 0.7$.

Larger driving amplitudes are associated with larger correlation lengths, producing a peak at slightly lower values of $D$. A detailed quantification of the dynamical role of multibreather excitations [9, 12, 13] would be a natural topic for future studies.

Finally, the calculated correlation functions allow us to readily compute the system response when the driving force acting on each oscillator is not staggered but spatially uniform, i.e. $M(t) = \sum_{n=1}^N x_n(t)$. The dotted line in Fig. 5 shows that the spectral amplification is very similar to that when breather formation was strictly forbidden (the case $k = 0$ shown in Fig. 1), lacking the stronger peak at lower noise levels. As expected from the deterministic analysis, this uniform driving force is very ineffective in boosting breather formation.

Summary. We have demonstrated the spontaneous formation of breathers in a hard $\phi^4$ lattice subject to a staggered driving force. The SR mechanism is different from the one observed in the paradigmatic Brownian particle in a bistable potential. Here, instead of a stochastic synchronization between noise-induced hopping events and the frequency of the external driving, the formation of noise-induced breathers with the selected driving frequency is optimized for a given level of fluctuations such that the average energy per particle matches the intrinsic energy of the breather mode. Further, this effect is shown to be suppressed if a spatially-uniform driving is used instead of a staggered one. We expect that the results reported in this paper may be useful for the generation and manipulation of breathers in many practical situations, and to be independent of dimension and of the specific nature of the nonlinearity, provided that the model is monostable.

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[24] This can be done in settings similar to those of Ref. 23, by changing the signal and ground leads in every other resistor leading to a diode in the configuration (L.Q. English, private communication).