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CNLS SCIENCE ACTIVITY

Sine-Gordon Soliton Behavior in Inhomogeneous Media

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ABSTRACT

We study sine-Gordon kink propagation in spatially periodic media. We present results of numerical simulations which are not compatible with earlier predictions of a radiative threshold. We carry out a perturbative calculation which helps interpret our numerical results and those earlier predictions in a physically correct way. We conclude by summarizing the general physical framework that arises from our study.

The study of nonlinear disordered systems is now recognized to be fundamental from the viewpoint of both basic mathematical theory and applications. Consequently, a great deal of research has been devoted to this topic [1–3]. A major part of this body of work has been concerned with a few archetypes that are amenable to analytical treatment while capturing some essential physics. The sine-Gordon (sG) and nonlinear Schrödinger (NLS) equations are often chosen to play this rôle of "canonical" examples. The reason is twofold. On the one hand, both of them are completely integrable and hence their well-known mathematical structure yields a good starting point for theoretical work; on the other hand, they accurately describe a large number of phenomena that occur in quasi-one-dimensional physical systems. In the context of these two models, disorder is introduced through suitably chosen perturbation terms (see [2] for an extensive list of physically relevant perturbations).

In the last few years we have been studying the behavior of nonlinear systems when perturbed by a spatially periodic potential. As a preliminary step to the investigation of sG breather dynamics [4] on these kind of potentials, it is natural to seek first a good understanding of kink dynamics in such media. Therefore we undertook that study, both analytically and numerically. Somewhat unexpectedly, we were led to some important new conclusions. First, we found no numerical evidence for a radiative divergence of kinks that was expected in view of several existing analytical calculations [6–8]. Second, we carried out an improved perturbative calculation that agrees with the simulations, as the proposed instability can be shown to be unphysical; besides earlier results are clarified. Third, we found that, opposite to what was believed to date, sG kink dynamics on a periodic potential is essentially that of a (relativistic) particle. A more detailed report on these results as well as on the occurrence of length scale competition in this system may be found elsewhere [9]. The great relevance of these results comes from the fact that for many nonlinear systems of physical interest only perturbative results are available. Therefore, as they are subject to pitfalls similar to those we describe here, all non-numerically validated or non-physically interpreted predictions should be treated with a degree of caution.

We start by describing the picture of sine-Gordon kink propagation on periodic potentials that has been accepted to date. It was shown by Mkrtchyan and Shmidt [6] and Malomed and Tribelsky [7,8] that, when kinks propagate in a system modeled by a perturbed sG equation of the form

$$u_{tt} - u_{xx} + [1 + \epsilon\cos(kx)]\sin u = 0, \qquad (1)$$

(modeling for instance a long Josephson junction with modulated critical current) there was a critical velocity $v_{\rm thr} = (1 + k^2)^{-1/2}$ such that kinks traveling with velocities $v < v_{\rm thr}$ did not emit any radiation at all, whereas in the opposite case the amount of emitted radiation decreased as $v \to 1$, diverging when $v = v_{\rm thr}$. This result was obtained by means of two quite different techniques: A Green-Function perturbation technique (GFPT) [6] and Inverse Scattering Perturbation Theory (ISPT) [7,8] (see also [2]). Malomed and Tribelsky [8] also showed that dissipation could play a regularizing rôle. but that leaves the question of the meaning of the divergence unanswered as regards Eq. (1). These authors were also able to compute the radiation characteristics: The radiation wavenumbers turned out to be related to the perturbation one by a complicated equation (see, e.g., [2]), which, in particular, implied that radiation is emitted with a non-intuitive wavenumber k^{-1} at the divergence. It has to be noted that it is very difficult to explain these results on the basis of the particlelike picture of kinks which has been much successful so far [10]; were these predictions true, the reason for them must come from the wave nature of kinks. We have only recorded here a short summary of previous work, and the reader is referred to the original papers [6–8] as well as to the review [2] for details.

With the above scenario (and the question it poses) in mind, we carried out a number of numerical simulations looking in the first place for the proposed threshold. We performed a careful search, paying attention to the fact that the predicted value was a first order calculation, and that it may not be quantitatively accurate. Hence, we monitored the amount of radiation emitted by the kink by making simulations with different initial conditions; if there was a threshold somewhere, there should be a change in the radiating power of the kink as it moved through it. The result was negative: No evidence for a threshold was found, even when the search was performed for a large range of initial velocities with a resolution of 10^{-2} for some choices of k. An example of the outcome of the simulations is shown in Fig. 1; other examples are shown in [9]. It has to be stressed that the predicted divergence

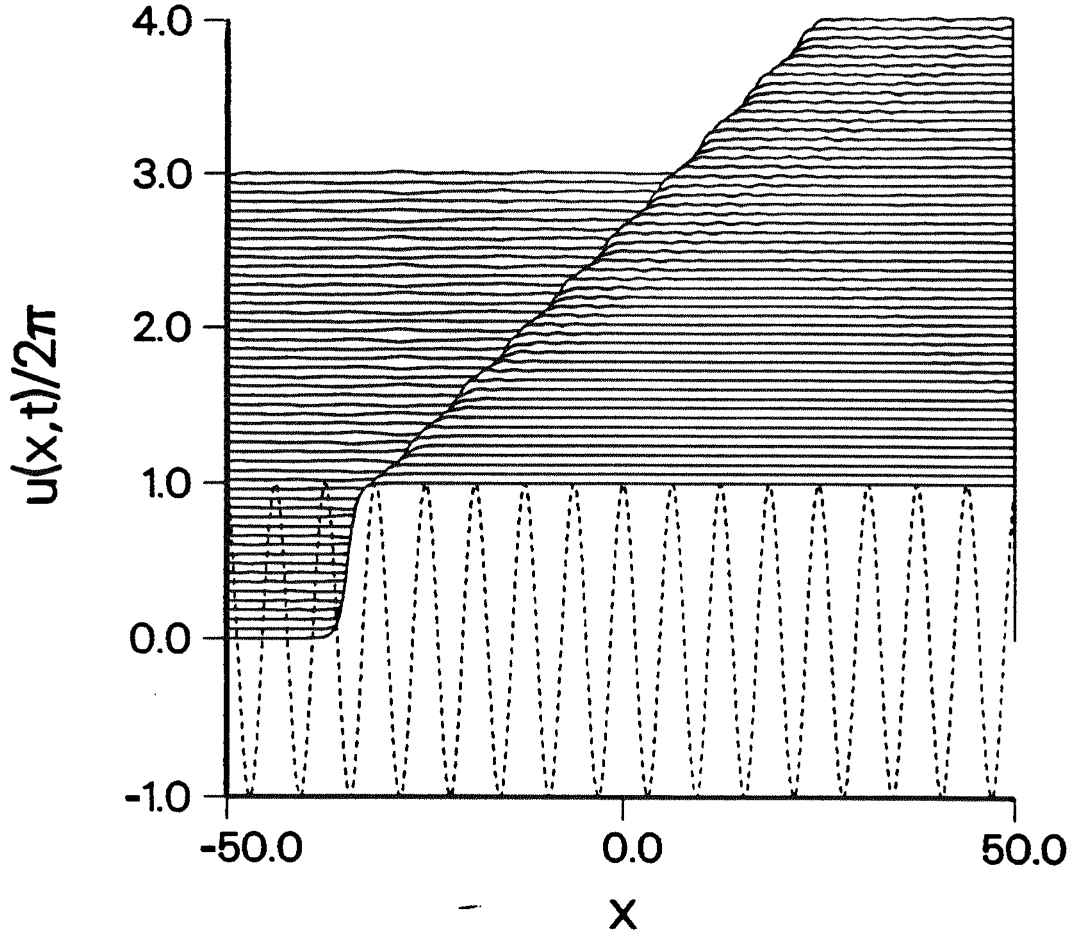

FIG. 1. Absence of divergence for kinks propagating in the spatially periodic sG model. Parameters are: $k = 1$, initial speed $v_0 = v_{\rm thr} = 2^{-1/2}$, $\epsilon = 0.5$. The amplitude of the emitted radiation is very small. Time increases upwards; final time $t = 100$. The potential is indicated by the dashed line (amplitude not to scale).

of the does not depend on the strength perturbing potential, ϵ, but we also tried to make the effect visible by increasing this parameter. Indeed, in Fig. 1, $\epsilon = 0.5$, a value that is not very small, and the kink seems unaffected except for a small amount of radiation and an oscillatory motion superimposed on its trajectory. On increasing ϵ further, trapping behavior takes place, i.e., kinks are trapped by the potential and cannot propagate, but there is not a strong emission of radiation (this last phenomenon can in fact be qualitatively understood by means of a collective coordinate approach [9]). Finally, we also observed that kinks always emit radiation, even when moving at a very low speed, far below the predicted threshold. It thus becomes evident that the features of kink propagation on periodic potentials are qualitatively different from the above perturbative analytical results.

In order to gain insight into the numerical observations, we developed a new perturbative approach for this problem. A detailed description of the technique can be found in [10]. Here we only quote the final result for our case, which can be obtained by particularizing Eqs. (5.9) of the second reference in [10] and lengthy algebra thereafter. The first order correction to a kink moving with constant velocity v is found as

$$u^{(1)}(x,t) = \frac{1}{8}\phi_b(t) f_b(x) + \int_{-\infty}^{\infty} d\kappa\ \phi(\kappa,t) f_\kappa(x) \tag{2}$$

where $f_b(t)$ and $f(\kappa,t)$ stand for the translation and radiative corrections, respectively, and the amplitudes $\phi_b(t)$ and $\phi(\kappa,t)$ are to be obtained from

$$\ddot{\phi}_b(t) = 4\int_{-\infty}^{\infty} dx\ \cos[k\gamma(x+vt)]\frac{\sinh x}{\cosh^3 x}, \tag{3a}$$

$$\ddot{\phi}(\kappa,t) + (1+\kappa^2)\phi(\kappa,t) = 2\int_{-\infty}^{\infty} dx\ \cos[k\gamma(x+vt)]\frac{e^{-i\kappa x}(\kappa - i\tanh x)}{\sqrt{2\pi(1+\kappa^2)}}\frac{\sinh x}{\cosh^2 x}, \tag{3b}$$

with v the speed of the unperturbed soliton and $\gamma \equiv (1-v^2)^{-1/2}$ the Lorentz factor.

The simplest part of Eqs. (3) is the first one: The translation mode contribution, Eq. (3a), is simply

$$\phi_b(t) = \frac{2\pi}{v^2\sinh(k\gamma\pi/2)}\sin(k\gamma v t). \tag{4}$$

Recalling that we are working in the unperturbed soliton reference frame, this is nothing but an oscillatory motion superimposed on its otherwise constant trajectory. This we already noted from the plot in Fig. 1; now, let us remark that the prefactor implies that short wavelength ($k \to \infty$) perturbations will have no effect on the motion of the center of the soliton, which is also in good agreement with our simulations in Fig. 2. This behavior can be understood in terms of a "smoothing" of the potential: The kink, having a width much larger than the perturbation wavelength, experiences only an effective averaged force, whose amplitude vanishes exponentially for large k (see related comments in [4,5]).

Equation (3b) for the κ-mode radiative contribution can also be solved. After computing the integral in the right hand side of Eq. (3b), one is left with an equation for a forced harmonic oscillator. This allows the determination of $\phi(\kappa,t)$, and to substitute for it in Eq. (2) to find the total radiative contribution:

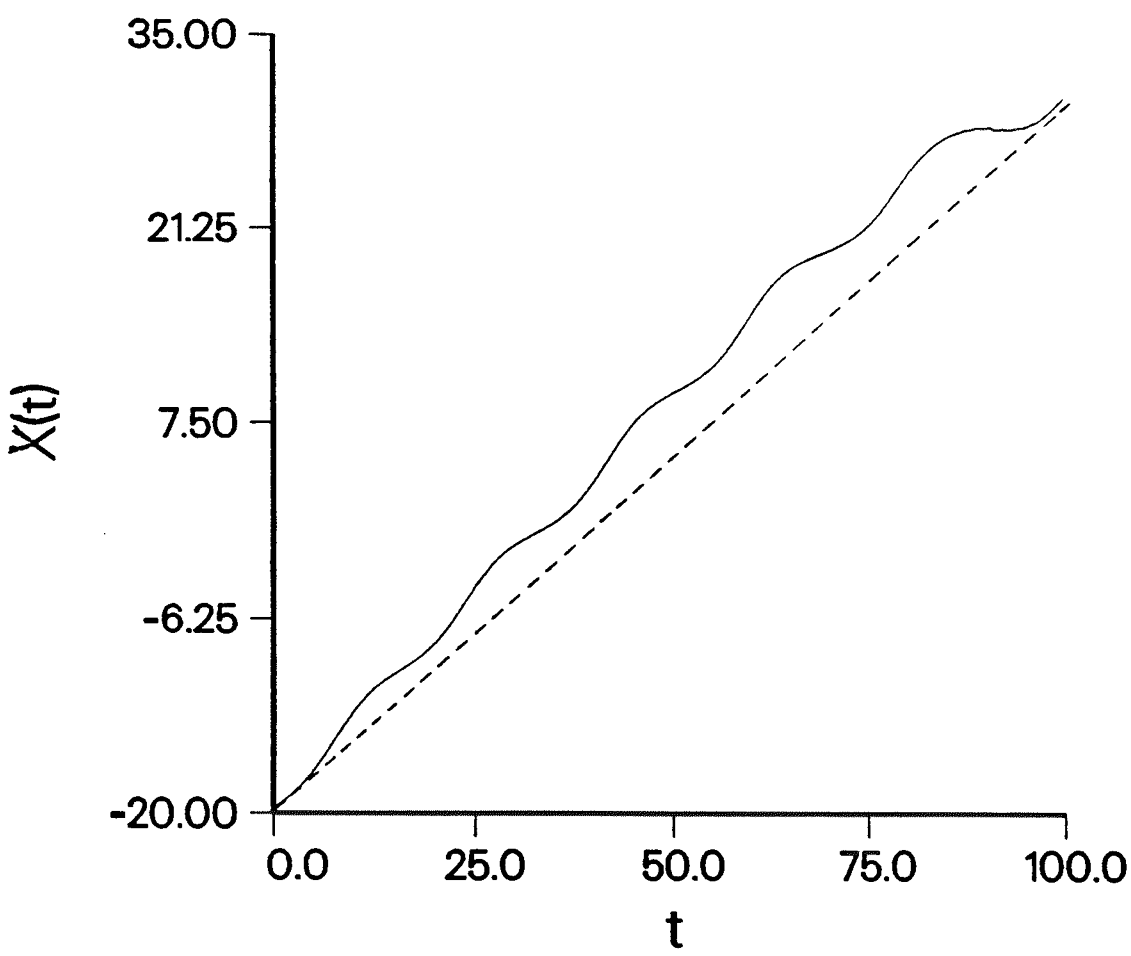

FIG. 2. Center of mass motion as obtained from simulations for a kink with initial speed $v = 0.5$ in a potential with $k = 0.2\pi$ (solid line) and (b) $k = 2\pi$ (dashed). Perturbation is large ($\epsilon = 0.7$) in both cases.

$$u^{(\mathrm{rad})}(x,t) \equiv \frac{1}{4}\left[\tanh x - \frac{\partial}{\partial x}\right] \times \tag{5}$$
$$\times \int_{-\infty}^{\infty} d\kappa \frac{1+\kappa^2 - k^2\gamma^2}{(1+\kappa^2)(1+\kappa^2-k^2\gamma^2v^2)} \left[\frac{e^{ik\gamma vt}}{\cosh[\pi(k\gamma-\kappa)/2]} + \frac{e^{-ik\gamma vt}}{\cosh[\pi(k\gamma+\kappa)/2]}\right] e^{i\kappa x}.$$

It is possible to deal with the integral in (5) in the complex plane; when $x > 0$, in the upper half plane, and when $x < 0$ in the lower half plane. The calculation is lengthy and the resulting expressions cumbersome. Here we simply outline it, discuss the pole structure, and summarize the physical interpretation. Full detail of the computation has been given elsewhere [9].

For the sake of definiteness, we take $x > 0$ (the opposite case is treated in the same way). Accordingly, the integral has to be analyzed in the upper half complex plane. The pole structure of the integrand is depicted in Fig. 3. All poles are simple, and their locations are $z_0 \equiv +i$, $z_1 \equiv i\alpha \equiv +i\sqrt{1-k^2\gamma^2v^2}$, and $z_n^{\pm} \equiv \pm\kappa\gamma + i(2n+1)$, $n = 0, 1, \ldots$ We treat them separately in the following.

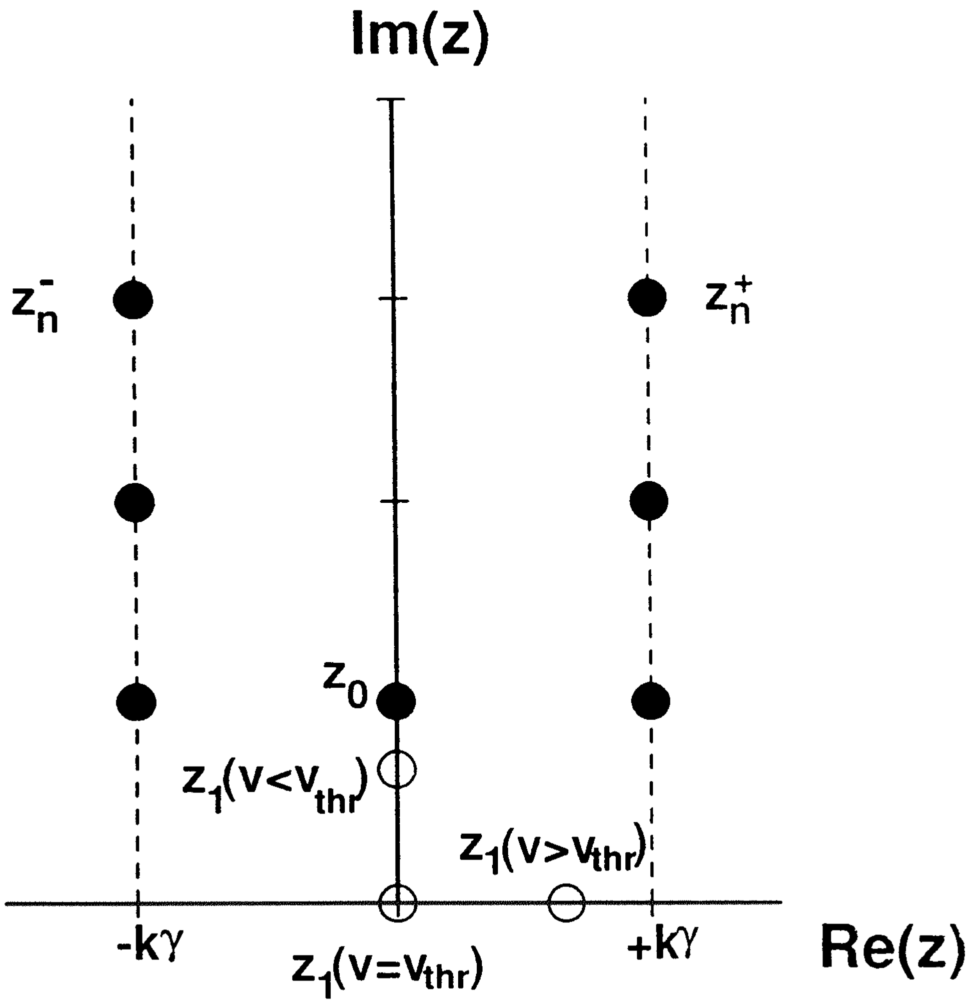

FIG. 3. The pole structure of the radiation contribution. Filled circles mark the location of the poles which give rise to corrections localized around the soliton. Empty circles denote the locations of pole z_1 as the speed change. Only when z_1 becomes real ($v > v_{\rm thr}$) it originates propagating wavelike corrections. See text for further explanation.

i. The first pole, z_0, is constant, and does not change when the parameters of the equation or the kink change. It is immediately seen that the contribution of the residue at z_0 is exponentially localized around the kink center, so this term does not give rise to any radiation, but rather to corrections of the kink shape

ii. The family of poles $z_n^{\pm}$ depends on the perturbation wavenumber k and on the kink velocity through the Lorentz factor γ. However, they always have a positive imaginary part. This again leads to exponentially localized contributions. Thus, the $z_n^{\pm}$ terms also do not produce any true radiative correction.

iii. The remaining pole is the key one. If $\alpha^2 \equiv 1 - k^2\gamma^2 v^2 > 0$, the same reasoning applied to the other poles holds, and there is no radiation. For fixed k, as v increases, the pole moves down along the imaginary axis, and at the critical value $v_{\rm thr} \equiv (1 + k^2)^{-1/2}$ it becomes 0. For kink velocities above $v > v_{\rm thr}$ the pole is purely real, and then it does give rise to a radiative contribution, whose form is given by (with $\beta \equiv i\alpha$ a real number)

$$u_\beta^{(\mathrm{rad})} \equiv \frac{1}{4}\left[\tanh x - \frac{\partial}{\partial x}\right] 2\pi i\,\mathrm{Res}(z_1) \tag{6a}$$

$$2\pi i\,\mathrm{Res}(z_1) = -i\pi\frac{1}{\gamma^2 v^2\beta}\left[\frac{e^{i(k\gamma vt+\beta x)}}{\cosh[\pi(k\gamma-\beta)/2]} + \frac{e^{-i(k\gamma vt-\beta x)}}{\cosh[\pi(k\gamma+\beta)/2]}\right]. \tag{6b}$$

To this point, it appears that our perturbative calculation leads exactly to the same prediction as those in [6,8], namely that here is a critical velocity $v_{\mathrm{thr}} \equiv (1+k^2)^{-1/2}$ below which kinks do not radiate and above which they do. At that precise velocity, the amplitude of the emitted radiation diverges; notice that β vanishes as v approaches v_{thr} from above and consequently the prefactor in Eq. (6b) goes to infinity. However, this is not so. The crucial difference arises when one looks more carefully at Eq. (6b): as v_{thr} is approached, not only the amplitude of the emitted wave diverges, but also its wavelength $2\pi/\beta$ (and its phase velocity $\omega \times 2\pi\beta$). Then, we are faced with something similar to an "infrared" divergence, and usually those do not have a real physical meaning. We will show inmediately that this is indeed the case here, but let us first comment on the reasons for our result being different from the previous ones. As to the GFPT computation [6], they compute the first order correction to the field much as we do here, but they do not use the natural translation mode-radiation basis, so they can not separate the different contributions and are therefore led to an expression they can not analyze in detail; they merely remark that their calculations are invalid in the vicinity of the divergence, as they assumed the correction should be small. On the other hand, ISPT [7,8] yields a different result than ours in spite of using a suitable basis because the integration over κ is made in an incoherent fashion, i.e., integrating over emitted energy instead of emitted amplitude (we notice in passing that many ISPT results are obtained by this same means). When the integration over radiation modes is made coherently as shown here, the result changes due to the superposition of modes. These reasons lead us to believe that the calculation we present here is the correct first order calculation.

Now that we have a reliable perturbative calculation, we have to understand what is the nature of the divergence we have found. To make progress, it is very important to turn to the form of our starting Eq. (1) *with dimensions*, namely

$$u_{tt} - c_0^2 u_{xx} + \omega_0^2[1+\epsilon\cos(kx)]\sin u = 0. \tag{7}$$

where c_0 and ω_0 are a velocity and a frequency characteristic of the particular physical context. Redoing the calculations with the dimensions transforms the divergence condition $k\gamma v_{\mathrm{thr}} = 1$ into $k\gamma_0 v_{\mathrm{thr}} = \omega_0$ ($\gamma_0 = (1-v^2/c_0^2)^{-1/2}$). This immediately clarifies what happens: The divergence occurs when the velocity of the kink is such that the time it takes to travel through a wavelength of the potential, $T_0 = \lambda/(\gamma v_{\mathrm{thr}})$, $\lambda = 2\pi/k$, is exactly the period of the lowest phonon, $T_0 = 2\pi/\omega_0$. If the velocity is lower than v_{thr}, the kink will not be able to excite phonons, whereas when its speed is higher it will and it will subsequently radiate. At v_{thr}, the excited radiation is that of the lowest phonon, and it has infinite wavelength and velocity, as predicted by our calculation. This natural picture of kinks exciting radiation according to the frequency of their propagation through a potential wavelength becomes therefore the likely candidate to explain the divergence. Interestingly, a similar reasoning can be applied to recent work on the ϕ^4 equation with spatially periodic potential [11] (it is important to stress that the perturbation theory there sums radiation modes coherently, see [12] for details), with the same good agreement to the critical velocity found. This clearly reinforces the interpretation we have just described.

In spite of the progress made so far, the most relevant question is not answered yet: Why numerical simulations do not agree with this calculation, which seems to allow for a simple and physically reasonable interpretation? By looking again at Fig. 1, it is easy to realize that the flaw of the perturbative calculation is at its very root: We are computing first order corrections around a kink moving at a *constant velocity* v, and this condition never holds. Whatever the starting position of the kink is, it will behave like a particle in the sense that it will be accelerated or decelerated depending on whether it travels towards a minimum or a maximum of the potential. In fact, the translation mode correction itself is telling us that: The kink velocity, in its reference frame, is not zero but rather it oscillates between positive and negative values. It is not a surprise, then, that first the resonance condition we have obtained is never matched, and second that the kink emits radiation at any velocity, because it is accelerating or decelerating. Of course, we should note that this is a perturbative calculation including only first order terms; the possibility still remains that the divergence is suppressed by higher order effects.

In conclusion, we have studied kink propagation on sG systems with a spatially periodic modulation of its characteristic frequency. We have shown numerically that kinks can propagate steadily and mostly undisturbed even for large amplitudes of the perturbation. Contradiction with analytical predictions previous to this work is resolved through a new perturbative calculation that allows us to understand why those predictions are not physically useful and why kinks do not show any divergence. The picture that emerges from this work is that, once again, sG kinks behave basically like particles and a collective coordinate approach can be more faithful than complicated perturbative results. In this respect, it has to be noted that a perturbative calculation describes everything beyond the center-of-mass dynamics: Extended (background) contributions (see, e.g., the third reference in [10]); shape changes localized around the (moving) kink; and real radiation, i.e., emission from the kink. It is crucial to separate and identify these physically different effects. Our results are likely to be general for kink-bearing models in view of the related results of [11]. Finally, we want to point out, as an important, general conclusion of this research, that perturbative calculations in nonlinear physics should be regarded as speculative if they are not verified through numerical simulations, and, most importantly, if their physical meaning is not fully established.

It is a pleasant obligation to thank Rainer Scharf and David Cai for enlightening discussions on this research. A.S. acknowledges a MEC(Spain)/Fulbright postdoctoral scholarship; he is also partially supported by DGICyT (Spain) project PB92-0378 and by the European Union Network on "Nonlinear Spatio-Temporal Structures in Semiconductors, Fluids, and Oscillator Ensembles." Work at Los Alamos is supported by the U.S. D.o.E.

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UPCOMING CNLS COLLOQUIA

Fri., Apr. 1	"Minimum Norm and Maximum Entropy Optimal Grid Image Reconstruction from Projections," Mark A. Limber, Simon Fraser Univ., 9:00 a.m., CNLS Conference Room
Fri., Apr. 1	"On Iterative Methods and Substructuring for Nonsymmetric Problems," Gerhard Starke, Karlsruhe Univ., 10:00 a.m., CNLS Conference Room
Fri., Apr. 1	"A New Method for Determining the Dynamics of Stochastic Processes," Lisa Borland, Univ. of California, Berkeley/Univ. of Stuttgart, 11:00 a.m., CNLS Conference Room, Joint CNLS/T-10 Seminar
Mon., Apr. 4	"Proteins as Paradigms of Complex Systems: Part I," Hans Frauenfelder, P-DO, 3:00 p.m., CNLS Conference Room
Tues., Apr. 5	"Proteins as Paradigms of Complex Systems: Part II," Hans Frauenfelder, P-DO, 3:00 p.m., CNLS Conference Room
Wed., Apr. 6	"A Novel Architecture for Computation at the Nanoscale," Seth Lloyd, T-13/CNLS, 3:00 p.m., CNLS Conference Room, followed by tea and cookies
Thur., Apr. 7	"A Thermal Lattice BGK Model without Nonlinear Deviations," Yu Chen, Univ. of Tokyo, 2:00 p.m., CNLS Conference Room, Joint CNLS/T-13 Seminar
Wed., Apr. 13	"On the Laser Ablation of Materials and its Applications," Jorge R. Sobehart, CNLS, 3:00 p.m., CNLS Conference Room, followed by tea
Tues., Apr. 19	"A Theory of Biomolecular Motors," Mark Millonas, CNLS/T-13 3:30 p.m., CNLS Conference Room
Wed., Apr. 20	"The Creation of Horseshoes," Toby Hall, Cambridge Univ., 10:00 a.m., CNLS Conference Room
Wed., Apr. 20	"Forced Generation of Solitary Waves in a Rotating Fluid and Their Stability," Wooyoung Choi, CNLS/T-7, 3:00 p.m., CNLS Conference Room, followed by tea
Wed., Apr. 27	"To Be Announced," Shanji Xiong, CNLS, 3:00 p.m., CNLS Conference Room, followed by tea

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93-4280	R. Camassa, "On The Geometry Of A Slow Manifold"
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94-0792 G. P. Berman and L. E. Portnov, "On The Solutions of the Differential Equations on Some Fractal Manifolds"

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94-0895 T. Grossman and Y. Davidor, "An Investigation of Genetic Operators for Continuous Parameter"

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94-0961 M. B. Mineev-Weinstein, "Conservation Laws In Field Dynamics Or Why Boundary Motion Is Exactly Integrable?"

94-1021 V. G. Makhankov, R. D. Jones, K. L. Buescher, K. Lee, M. Messina, D. W. Shevitz, M. Splichal and R. Caldwell, "Physical Features Of Plasma In Etching Reactors Reactive Ion Etching (RIE) Part I: The Bulk of Plasma Electrons"

94-1045 R. Farengo and J. R. Sobehart, "States of Minimum Energy Dissipation in Tokamaks Sustained By Helicity Injection"

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Title	Dates	Location	Technical Host
Rational and Irrational Approaches to Sequence Design	4/30-5/1//94	Santa Fe	A. Lapedes
Colorado Days	5/6-7/94	CNLS	B. Luce
Annual 14: Quantum Complexity in Mesoscopic Systems	5/16-20/94	Los Alamos	A. R. Bishop R. Ecke R. Mainieri
First-Order Systems Least-Square Functionals	5/25-27/94	CNLS	T. Manteuffel
Complex Systems Summer School	6/5-7/1/94	Santa Fe	E. Jen
Ocean Modeling Institute	7/11-22/94	CNLS	D. Holm
Frontiers of Geostrophic Turbulence	8/8-12/94	CNLS	B. Nichols S. Y. Chen
NEEDS '94	9/12-16/94	Los Alamos	V. Makhankov A. R. Bishop

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Ildar Gabitov, Landau Inst., mesoscale ocean dynamics modeling

Xiaoming Gao, Univ. of South Carolina, robust control techniques and neural networks

Jarmo Rantakokko, Uppsala Univ., data structure design for overlapping grid computer calculations

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