Numerical analysis of energy localization in ferromagnetic spin chain with the effect of impurity

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Abstract

Numerically we investigate the dynamics of energy localization in a ferromagnetic spin with the effect of external impurity in the semiclassical limit. We use the Glauber's coherent state method in combination with Holstein-Primakoff bosonic representation of spin operators for obtaining nonlinear difference differential equation in the form of the nonlinear Schrodinger equation which express the dynamics of ferromagnetic spin chains. We performed molecular dynamical simulation on nonlinear difference differential equation and obtain the existence of localized modes in ferromagnetic spin chain. The effect of discreteness and strength of impurity on localized modes is studied.

Key words: Molecular dynamical simulation, localized modes, ferromagnetic spins chain, effect of impurity.

I. INTRODUCTION

Generally, all systems have nonlinearity which means that the signature of a nonlinear dynamical system is the breakdown of the superposition principle [1]. The materials which have nonlinear properties are completely characterized by soliton wave or localized wave. In recent decades, the soliton excitation in nonlinear magnetic materials has been studied theoretically and experimentally in view of the fact that the progress in developing the technological important of magneto-optic recording and high density storage devices [2, 3]. Ref. (4-12) has been investigated the nonlinear spin excitation in the form of soliton in the Heisenberg model of ferromagnets with different kinds of magnetic spin interaction in the classical and semiclassical limit. In a nonlinear system, modulational instability (MI) is of elementary idea for the formation of localized excitations such as envelope solitons and intrinsic localized modes [13-16]. Kivshar et al. pointed out that the MI is a possible mechanism for the generation of localized modes in nonlinear lattice [13]. The dark type localized mode may exist in the system, if the MI does not present in the system. As a result, MI is a good candidate to understand the generation of localized modes in nonlinear lattices. In the past decade, Lai et al. and Nguenang et al. investigated the MI of the nonlinear waves in a ferromagnetic spin chain with magnetic interactions [16, 17]. Recently, MI of a plane wave in a discrete ferromagnetic spin chain with physically significant higher order dispersive octupole-dipole and dipole-dipole interactions was studied by Kavitha et al and they also investigated modulational instability and highly localized discrete breather modes in a one-dimensional discrete weak ferromagnetic lattice with on-site easy-axis anisotropy because of crystal field effect [18, 19]. Very recently, Bing Tang eta al investigated MI and localized modes in Heisenberg ferromagnetic chains with single-ion easy-axis anisotropy in the semiclassical limit. They found that the inclusion of the single-ion anisotropy affects significantly the shape of the region of modulational instability [20]. However, to our knowledge, energy localization in ferromagnetic spin chain with impurities has not been reported in the literature. Therefore, in this paper we are investigating the localized modes in ferromagnetic spin chain in the semiclassical limit. The structure of the paper is as follows. In section II, we consider a classical Heisenberg ferromagnetic spin chain with presence of impurity and also formulate the discrete dynamical equation for the ferromagnetic spin chain with the help of Holstein-Primakoff transformation and Glauber's coherent state representation. The molecular dynamical simulation has carried out for the discrete dynamical equation and also explores the strength of impurity on localized modes in ferromagnetic spin chain in section III. The results are presented in section. IV.

II. MATHEMATICAL BACKGROUND OF FERROMAGNETIC SPIN CHAIN WITH IMPURITY

We consider a one-dimensional ferromagnetic chain of **N** spins which are coupled through both Heisenberg exchange interaction with impurity. We start with a spin Hamiltonian describing the ferromagnetic spin chain with impurity [21]

$$H = -J\sum_n \vec{s}_n\vec{s}_{n+1} - (A+\varepsilon\delta_{n,n_0})\sum_n (s_n^z)^2 - \mu H_0 \sum_n s_n^z. \tag{1}$$

Here, the first term represents the ferromagnetic (**J** > 0) Heisenberg exchange interaction between the neighbouring spin vectors and **J** is the short range nearest neighbour exchange coupling constant and **A** is the on-site anisotropy constant which can be positive (easy axis) or negative (easy plane). $\mathbf{H_0}$ is the external magnetic field applied along the z-axis, so that in the ground state of the system all spins are aligned in the z-direction and **μ** is the magnetic moment per spin. **ε** describes an impurity to the anisotropy placed at the position $\mathbf{n_0}$ and can be of arbitrary sign and strength. In order to investigate the magnetic properties of the above system, we make use of the Holstein-Primakoff transformation combined with the Glauber's coherent state representation for the bosonic operators [22, 23] in Eq. (1), and then we have

$$i\frac{du_n}{dt} = -J\left[\begin{array}{l} \alpha^2(u_{n+1}+u_{n-1}-2u_n) - \dfrac{\alpha^4}{4}[2|u_n|^2(u_{n+1}+u_{n-1}) + u_n^2(u_{n+1}^*+u_{n-1}^*) \\ +(|u_{n+1}|^2 u_{n+1} + |u_{n-1}|^2 u_{n-1}) + 2u_n(|u_{n+1}|^2 + |u_{n-1}|^2)] + \dfrac{\alpha^6}{16}[(|u_{n+1}|^2 \\ u_{n+1}^* + |u_{n-1}|^2 u_{n-1}^*)u_n^2 + 2|u_n|^2(|u_{n+1}|^2 u_{n+1} + |u_{n-1}|^2 u_{n-1})] \end{array}\right] -$$

$$[A+\varepsilon\delta_{n,n_0}][2\alpha^4|u_n|^2 u_n - \alpha^2 u_n] + \mu H_0\alpha^2 u_n. \tag{2}$$

Equation (2) shows that the spin dynamics of a ferromagnetic spin chain with effect of impurity under semiclassical approximation. The structure of Eq. (2) is also resembles the well known discrete nonlinear Schrödinger (DNLS) equation, from which we can study the complete dynamics of spin under the impurity effect with the help of molecular dynamical simulation in the next section.

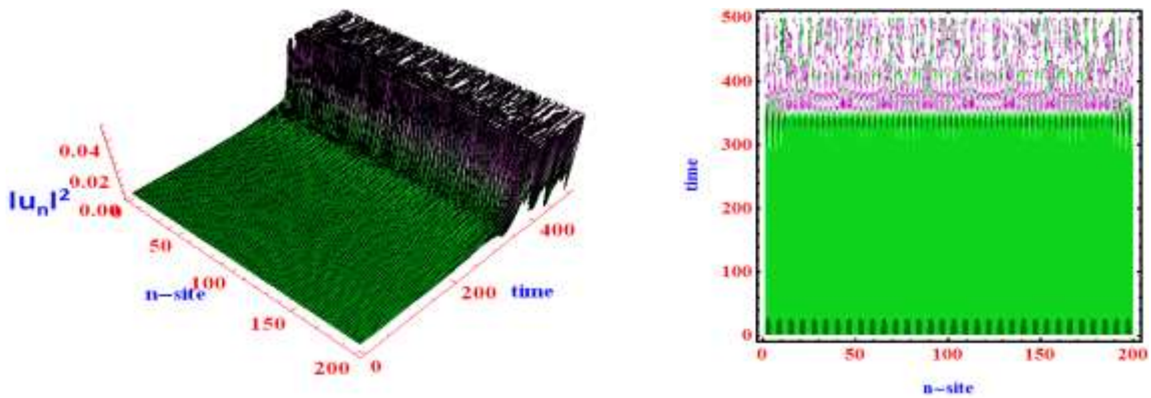
III. MOLECULAR DYNAMICAL SIMULATION OF DNLS EQUATION WITH EFFECT OF IMPURITY

We demonstrate the molecular dynamical simulation in order to analysis the existence of localized modes in ferromagnetic spin chains [24, 25]. Using the fourth-order Runge-Kutta method, we wrote program for Eq. (2) and also assumed that the chain of N = 200 units with periodic boundary conditions. The initial conditions of modulated nonlinear spin wave of the form

$$\begin{aligned} u_n(t) &= (u_0 + 0.01\cos(Qn))\cos(kn), \\ \dot{u}_n(t) &= (u_0 + 0.01\cos(Qn))\omega\sin(kn). \end{aligned} \tag{3}$$

Where k is the wave vector is defined modulo 2π in the lattice and chosen in the k = (2π l/N) and Q is modulated wave as chosen (2π L/N). The l and L are integers lower than N/2.

(a) Ɛ = 1



(b) Ɛ = 1.7

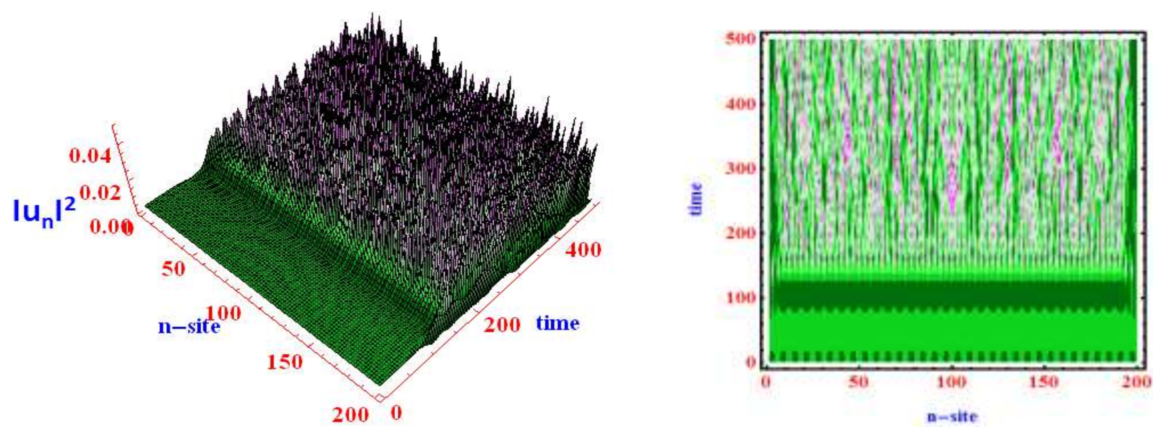


Figure 1: Evaluation of energy density plot with choice of parameters are J = 0.2, A = 0.5, H = 0.2 and μ =0.01

After the execution of the program, we obtain the temporal evolution of the energy density plot for various values of the impurity parameter ε as shown in Fig. 1(a-b). From Figs. 1(a-b), the horizontal axis indicates the position along the lattice points and the vertical axis corresponds to the time. The minimum intensity of localized modes indicated as green color while pink with white color indicating the maximum intensity of localized modes. In this study, arbitrarily we choose the impurity value for the purpose of analyze the existence of localized modes in ferromagnetic spin chain. In Fig. (1a), the strength of impurity fixed as $\boldsymbol{\varepsilon}$ =1 and found that uniform mode of the wave excited with high amplitude at time t = 340. Initially, the uniform wave is stable until 340 units of time and then wave gets breaks up into strong localized modes which are fairly uniformly spaced with the spatially periodic pattern. Surprisingly, we found that when we increased strength of impurity ($\boldsymbol{\varepsilon}$ =1.7) on material, instability of localized modes breaks up faster than the previous case and a similar breakup of the uniform mode happens at 140 units of time. At the initial time of excitation of localized modes is not interacting themselves (see counter plots of Fig. 1(a-b)) and after the sometime the modes are interacting which is continuing at the end of the time. Therefore, the effect of impurity induces the strong localized modes and also understood the behavior of localized modes in ferromagnetic spin.

IV. CONCLUSION

We have investigated the existence of energy localization along ferromagnetic spin with the strength of impurity. The nonlinear difference of differential equation is obtained from Heisenberg Hamiltonian by the use of Glauber's coherent state method in combination with Holstein-Primakoff transformation. The dynamics of ferromagnetic spin chains is described by the nonlinear difference of a differential equation is the form of the nonlinear Schrodinger equation. By the use of molecular dynamical simulation, we studied the existence of localized modes in a ferromagnetic spin with the effect of impurity. The existence as well as the behaviour of localized modes depends on the strength of the impurity on ferromagnetic spin. These results are to conclude that discreteness and strength of impurity support the existence of localized modes in ferromagnetic spin chains.

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