Chinese Journal of Physics 55 (2017) 1103–1114

Contents lists available at ScienceDirect

Chinese Journal of Physics

journal homepage: www.elsevier.com/locate/cjph

Kink-like excitations in a square lattice model of an antiferromagnetic spin system

T. Evangeline Rebecca, M.M. Latha*

Department of Physics, Women's Christian College, Nagercoil, 629 001, India

ARTICLE INFO

Article history:
Received 5 September 2016
Revised 24 December 2016
Accepted 17 April 2017
Available online 7 June 2017

Keywords:
Antiferromagnet
Multiple exponential method
Spin Hamiltonian
Soliton

ABSTRACT

Introducing the Holstein–Primakoff (H-P) bosonic representation of spin operators, the coherent state ansatz and the time dependent variational principle, the dynamics of the square lattice model of an antiferromagnetic system is studied. The dynamics is found to be directed by a set of coupled nonlinear partial differential equations. Employing the multiple exponential function method, soliton excitation in the system is studied. Multiwave kink soliton solutions and their interaction properties are analysed.

1. Introduction

Most physical systems are nonlinear in nature, which means that the signature of a nonlinear physical system is the breakdown of the superposition principle [1]. Such systems are prevalent in science and widely studied in areas such as engineering, physics, life sciences and so on. Often the systems have parameters which when varied can result in a widely different dynamical behaviour for the system and gives rise to rich nonlinear behavior in which stable bound states can prevail on a classical, as well as quantum mechanical, level, and the aforesaid bound states are called solitons. Soliton theory is an interdisciplinary topic which enacts an important role and has been conjointly benefited in the field of physics such as solid-state physics, condensed matter physics, mathematical physics and particle physics. Soliton research interests span from theoretical aspects, such as soliton existence, the computation of soliton profiles and soliton stability theory, through aspects such as soliton dynamics and soliton interactions and application aspects. Indeed, the number of nonlinear materials that are fully characterized by soliton equations and the types of solitons discovered in them seems to be steadily growing. In the recent past, as soliton research is prolific in the field of magnetics, nonlinear dynamical excitations of magnetic ordered materials have represented the traditional objects of experimental and theoretical studies in which magnetic solitons are exposed [2,3].

Solitons, as nonlinear excitations of magnetic systems, have been studied extensively in the classical and semiclassical limit during the past four decades [4–7]. In the classical approach [8–12], single-soliton solutions are obtained for a continuum version of the classical linear Heisenberg chain. In a quantum spin system, the soliton solution is studied using a bosonic representation of the spin operators. In a spin-coherent representation, one can work directly with the operators, make no approximation to the Hamiltonian, and develop an exact nonlinear equation for the quantum system [12,13]. The other coherent state treatments [14–18] use a truncated Holstein–Primakoff (H-P) expansion [19] for $S_j^{\pm}$ and further

* Corresponding author.
E-mail address: lathaisaac@yahoo.com (M.M. Latha).

http://dx.doi.org/10.1016/j.cjph.2017.04.015
0577-9073/

approximate the Hamiltonian to be biquadratic in boson operators. Working in the coherent state representation of Glauber [20], one can find solitary wave profiles identical to classical solitons, this is the so-called semiclassical treatment, which is a very suitable method for studying soliton excitations because of its validity and consistency. Very recently Latha et al. [21,22] have reported works on the higher dimensional ferromagnetic spin system.

In particular, for the last few years, nonlinear wave phenomena of an antiferromagnet has been progressively investigated in the general context of 'Nonlinear Science' [23,24]. The nonlinear solitary wave excitations in a one-dimensional AFM has been vigorously evaluated by many researchers [25–32]. Liu and Zhou [33] studied the solitary excitations in an order-parameter-preserving AFM, using a coherent-state ansatz. In recent years there has been much interest in the static and dynamic properties of two-dimensional magnetic systems, as they support interesting nonlinear excitations including solitons and vortices. It is also well established that a large class of classical spin models, including the 2D Heisenberg model, support nonlinear topological excitations. Recent theoretical and experimental studies confirm the existence of solitons and their dominance in the thermodynamics of a nearly classical 2D Heisenberg antiferromagnet [34]. The elementary excitations for the 2D quantum Heisenberg antiferromagnet was investigated by Chen et al. [35] using the projector quantum Monte Carlo method. Pereira and Pires [36] analysed the solitons in the presence of a static spin vacancy on a 2D Heisenberg AFM, and found that the effective interaction between the defects is attractive for small distances of separation and repulsive for larger separations; also, for the case in which the spin vacancy is located at the soliton center, they found that besides the Belavin–Polyakov soliton another type of soliton is possible, and its configuration, energy and size were obtained. Subbaraman et al. [37] introduced a very small amount of nonmagnetic impurity into the magnetic sites of a classical 2D AFM and have detected a small, pinned soliton that tends to form at the nonmagnetic impurity in the layered antiferromagnet.

But so far the Hamiltonian associated with the square lattice model of an antiferromagnetic spin system and studies related to it have not yet been reported in the literature. Motivated by this, in this paper, we propose a non-integrable lattice model of the Heisenberg AFM spin chain. We study the soliton dynamics by constructing the equations of motion after averaging the Hamiltonian using a suitable wave function for the spin system. We use the exponential function method to find the multiwave soliton solutions.

This paper is organized as follows. In Section 2, we consider the model Hamiltonian and derive the equations of motion. In Section 3, the multiple exponential function method is employed to study the complete nonlinear soliton excitations of the above system. Section 4 deals with the construction of two kink soliton solutions. Section 5 deals with the formation of three wave solitons and their interactions. Finally our conclusions are addressed in Section 6.

2. Model Hamiltonian and equations of motion

In our model, we consider an antiferromagnetic lattice which is divided into two interpenetrating sublattices A and B. Considering only the nearest neighbour interactions, the Heisenberg Hamiltonian describing the AFM spin system is written as

$$\tilde{H} = \sum_{i,j}[\tilde{J}_1(\vec{S}^A_{i,j}.\vec{S}^B_{i,j}) + \tilde{J}_2(\vec{S}^A_{i+1,j}.\vec{S}^B_{i,j}) + \tilde{J}_3(\vec{S}^A_{i,j+1}.\vec{S}^B_{i,j}) + \tilde{J}_4(\vec{S}^A_{i+1,j+1}.\vec{S}^B_{i,j})] + A[(S^{Az}_{i,j})^2 + (S^{Bz}_{i,j})^2], \tag{1}$$

where $\tilde{J}_1$ represents the coefficient of the nearest neighbour interaction. $\tilde{J}_2$, $\tilde{J}_3$ correspond to the coefficients of bilinear exchange interactions along the x and y- directions, respectively. $\tilde{J}_4$ refers to the coefficient of the neighbouring interaction along the diagonal. A represents the anisotropy parameter. The spin Hamiltonian (1) can be expressed in the dimensionless form [38] by introducing the dimensionless spin $\hat{S}_{i,j} = \vec{S}_{i,j}/\hbar$ and by defining $\hat{S}^{\pm}_{i,j} = \hat{S}^x_{i,j} \pm i\hat{S}^y_{i,j}$. The Hamiltonian now becomes

$$\begin{aligned} H = \sum_{i,j}\Bigg[&\frac{J_1}{2}[\hat{S}^{A+}_{i,j}.\hat{S}^{B-}_{i,j} + \hat{S}^{A-}_{i,j}.\hat{S}^{B+}_{i,j} + 2(\hat{S}^{Az}_{i,j}.\hat{S}^{Bz}_{i,j})] + \frac{J_2}{2}[\hat{S}^{A+}_{i+1,j}.\hat{S}^{B-}_{i,j} + \hat{S}^{A-}_{i+1,j}.\hat{S}^{B+}_{i,j} + 2(\hat{S}^{Az}_{i+1,j}.\hat{S}^{Bz}_{i,j})] \\ &+ \frac{J_3}{2}[\hat{S}^{A-}_{i,j+1}.\hat{S}^{B+}_{i,j} + \hat{S}^{A+}_{i,j+1}.\hat{S}^{B-}_{i,j} + 2(\hat{S}^{Az}_{(i,j+1)}.\hat{S}^{Bz}_{i,j})] + \frac{J_4}{2}[\hat{S}^{A-}_{i+1,j+1}.\hat{S}^{B+}_{i,j} + \hat{S}^{A+}_{i+1,j+1}.\hat{S}^{B-}_{i,j} + 2(\hat{S}^{Az}_{i+1,j+1}.\hat{S}^{Bz}_{i,j})]\Bigg] \\ &+ A[(S^{Az}_{i,j})^2 + (S^{Bz}_{i,j})^2]. \end{aligned} \tag{2}$$

While writing Eq. (2), we have defined $H = \tilde{H}/\hbar^2$; $J = \tilde{J}$; $J_1 = \tilde{J}_1$; $J_2 = \tilde{J}_2$; $J_3 = \tilde{J}_3$; $J_4 = \tilde{J}_4$. We bosonize the Hamiltonian by using the Holstein–Primakoff (H-P) representation of spin operators given by [19]:

$$\begin{aligned} S^{A+}_{i,j} &= (2S - a^\dagger_{i,j}a_{i,j})^{\frac{1}{2}}a_{i,j}, \\ S^{A-}_{i,j} &= a^\dagger_{i,j}(2S - a^\dagger_{i,j}a_{i,j})^{\frac{1}{2}}, \\ S^{A}_{(i,j)z} &= S - a^\dagger_{i,j}a_{i,j}, \end{aligned} \tag{3}$$