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Spin gap in coupled magnetic layers

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HIGHLIGHTS

- Two coupled $S = 1/2$ quantum spinchains are examined.
- Quasiparticles with generalized spin are introduced.
- Surface effects are eliminated.
- Formation of energy gap is verified.
- Emergence of generalized spin polarization for ground state.

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ABSTRACT

Quantum spinchains are often used to model complex behavior in condensed matter systems that display long range correlations. When two or more quantum spinchains interact, they also exhibit spin transport and model finite nanomagnetic layers. Here, we investigate properties of two coupled $S = 1/2$ quantum spinchains in the finite limit, where spurious surface artifacts are present. Our results show the introduction of new fermionic modes with one additional degree of freedom eliminates the artifacts, in an effective one-dimensional finite lattice. In this setting, the mean field approximation is robust and enables the evaluation of energy levels and the energy gap. Moreover, quasiparticle polarization due to interchain coupling is verified and explains the emergence of spin polarization in uniform materials.

1. Introduction

Simultaneous control of both electric and spin currents is the main goal in the development of new and efficient semiconductor devices. The flow of electronic spin, or spin current, adds one extra degree of freedom to information storage mechanisms and also allows new methods to manipulate the electron dynamics. Multilayered magnetic materials, which exhibit spin currents, have already found several scientific and technological applications such as spin valves [1] and tunneling magnetic junction [2,3]. So far, injection of electric currents through asymmetrical magnetic layers has been the standard way to control spin density near interfaces [4–6]. Injection of spin polarized electric currents in adjacent ferromagnetic layers gives rise to spin torque [7] and spin pumping [8] phenomena.

The spin torque also occurs with non-polarized currents in materials with strong spin–orbit interaction [9] such as (Ga,Mn)As. These materials possess fairly uniform chemical composition, avoiding additional lithographic patterns

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altogether, thus, easier to integrate current technologies. This example illustrates that both material composition and interactions are relevant to observation of spin currents or spin related effects. Interactions become even more relevant in the nanometric regime, where surface effects are comparable to bulk contributions. As consequence, the band structure is also modified in the finite regime, leading to corrections to spin transport properties as well. In addition, the finite size of magnetic layers or nanostructures imposes strong constraints to the wave functions and long range correlations [10].

Here, we study two interacting quantum spinchains as a surrogate for a magnetic bilayer, exploiting the fact their dynamics should be similar for very small lattice sizes. Our goal is to extract the microscopic conditions and constraints that allow the development of spin current and spin polarization between two distinct uniform layers. We consider a fermionic model with $m = 2$ interacting $S = 1/2$ quantum spinchains, R_1 and R_2, with L sites each, subjected to periodic boundary conditions and separated by a spatial distance d. They constitute a *ladder* or quasi-unidimensional spinchain [11]. This class of composite system has a rich physical content [12–16], where spin–spin spatial correlation depends on the number m of chains [17] and the interaction between the spinchains promotes variations in magnetization for each lattice. The Jordan–Wigner fermionization procedure [18] is employed to map the local dynamics within each spinchain. In this procedure, localized spin operators are transformed into spinless fermions operators and the interchain interaction is modeled as the exchange of spinless fermions. To describe the underlying dynamics of coupled spinchains, we identify the relevant fermionic modes, which possess one additional degree of freedom similar to the spin, σ, associated with the $\bar{J} = 1$ deformed angular momentum. The energy levels are calculated and the emergence of an energy gap ΔE_g is observed, in the mean field (MF) approximation. For non-vanishing coupling λ, the ground state exhibits spontaneous σ-polarization.

2. The model

Quantum spinchains are one-dimensional periodic lattices in which each site $k = 1, 2, \ldots, L$ holds localized spin operators, S_k^α ($\alpha = x, y, z, \pm$). They are often used to model magnetism in matter since they are able to produce long range correlation [19], as verified from their epitaxy [20,21]. These strongly correlated systems are usually associated with cooperative phenomena and critical phase transitions. Such critical phases are characterized by gapless eigenspectra, providing long range correlations. For finite quantum systems, the energy spectra also depend on parity the of L [20], tying lattice size with magnetic ordering and the characterization of spin currents and spin mobility [22]. Moreover, the number m of coupled spinchains also affects the existence of the energy gap. From Haldane conjecture [23,24], valid for spin $S \gg 1$, it is often inferred $S = 1/2$ ladders have a non-null energy gap for m even [25,26], gapless otherwise.

Among the various quantum spinchains available, the most well-known is the $S = 1/2$ Heisenberg model (HM). In the HM, the local spin–spin coupling mimic the Coulomb interactions, explaining the magnetic ordering of ground state and the emergence of long range order. The HM hamiltonian is:

$$H_{\mathrm{HM}} = -\frac{J}{2}\sum_{k=1}^{L}\left[\sigma_k^x\sigma_{k+1}^x + \sigma_k^y\sigma_{k+1}^y + \Delta\sigma_k^z\sigma_{k+1}^z\right], \tag{1}$$

where σ_k^a ($a = x, y, z$) are the localized Pauli matrices, J is the exchange interaction coupling and $\Delta \in \mathbb{R}$ is the axial anisotropy. The case $\Delta = 0$ is the planar XY model, while $\Delta = 1$ is the ferromagnetic (antiferromagnetic) Heisenberg model for $J \geqslant 0$ ($J \leqslant 0$). The axial anisotropy plays an important role in any magnetic environment as isotropic systems are unable to establish long-range correlations for any temperature [27,28]. Another outstanding feature is the exact solution via Bethe *ansatz* [29]. In particular, for the coupling range $|\Delta| < 1/2$ the HM is critical and the system exhibits long range order. The coupled $S = 1/2$ quantum spinchain model considered in this study takes the HM as foundation, inheriting many of the mathematical methods and physical properties. In what follows, we describe the model, the coupling mechanisms and the striking finite size effects.

Let R_i ($i = 1, 2$) label two quantum spinchains, both containing L site and distant from each other by a spatial distance d and periodic boundary conditions, as Fig. 1 depicts. In analogy to HM, we define the operators σ_{ik} for spinchain R_i at site $k = 1, \ldots, L$. For large d, the interchain coupling vanishes. Therefore, the intrachain interactions H_i are described by the HM with the following modifications: $\Delta \to \Delta_i$ and $\sigma_k\sigma_{k+1} \to \sigma_{ik}\sigma_{ik+1}$ for each chain R_i,

$$H_i = -\frac{J}{2}\sum_{k=1}^{L}\left[\sigma_{ik}^x\sigma_{ik+1}^x + \sigma_{ik}^y\sigma_{ik+1}^y + \Delta_i\sigma_{ik}^z\sigma_{ik+1}^z\right]. \tag{2}$$

As R_1 and R_2 are brought together, the interchain interactions become more relevant. If the system develops an energy gap during this process, as hinted by Haldane conjecture, the Jordan–Wigner (JW) fermionic approach [18] is a suitable method. The main idea in the JW transformation is to obtain a new set of fermionic operators c_{ik} and $c_{ik}^\dagger$ from σ_{ik}^- and σ_{ik}^+, respectively, with $\sigma_{ik}^\pm = (\sigma_{ik}^x \pm \imath\sigma_{ik}^y)/2$. The fermionic behavior requires the anticommutation rule $\{c_{ik}, c_{jl}^\dagger\} = \delta_{ij}\delta_{kl}$ whereas the $\sigma_{ik}^\pm$ operators share both fermionic and bosonic rules. Hence, the JW transformation removes any bosonic contribution from site operators, which is the necessary condition to the proper interpretation of new fields c_{ik} as fermions. Despite the well-defined algebraic relations, the new particles are constructed from the physical spin and therefore lack internal degrees of freedom. Due to this observation, the JW fermions are spinless fermions. The spinless fermionic destruction operator c_{1k},