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Monte Carlo determination of the low-energy constants of a spin-$\frac{1}{2}$ Heisenberg model with spatial anisotropy

F.-J. Jiang,1,* F. Kampfer,2 and M. Nyfeler1

1Center for Research and Education in Fundamental Physics, Institute for Theoretical Physics, Bern University, Sidlerstrasse 5, CH-3012 Bern, Switzerland
2Department of Physics, Condensed Matter Theory Group, Massachusetts Institute of Technology (MIT), 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

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Motivated by the possible mechanism for the pinning of the electronic liquid crystal direction in YBa2Cu3O6.45 as proposed by Pardini et al. [Phys. Rev. B 78, 024439 (2008)], we use the first-principles Monte Carlo method to study the spin-$\frac{1}{2}$ Heisenberg model with antiferromagnetic couplings $J_1$ and $J_2$ on the square lattice. In particular, the low-energy constants spin stiffness $\rho_s$, staggered magnetization $M_s$, and spin wave velocity $c$ are determined by fitting the Monte Carlo data to the predictions of magnon chiral perturbation theory. Further, the spin stiffnesses $\rho_{s1}$ and $\rho_{s2}$ as a function of the ratio $J_2/J_1$ of the couplings are investigated in detail. Although we find a good agreement between our results with those obtained by the series expansion method in the weakly anisotropic regime, for strong anisotropy we observe discrepancies.

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I. INTRODUCTION

Understanding the mechanism responsible for high-temperature superconductivity in cuprate materials remains one of the most active research fields in condensed-matter physics. Unfortunately, the theoretical understanding of the high-$T_c$ materials using analytic methods as well as first-principles Monte Carlo simulations is hindered by the strong electron correlations in these materials. Despite this difficulty, much effort has been devoted to investigating the properties of the relevant $t$-$J$-type models for the high-$T_c$ cuprates.1–4 Although a conclusive agreement regarding the mechanism responsible for the high-$T_c$ phenomena has not been reached yet, it is known that the high-$T_c$ cuprate superconductors are obtained by doping the antiferromagnetic insulators with charge carriers. This has triggered vigorous studies of undoped and lightly doped antiferromagnets. Today, the undoped antiferromagnets on the square lattice such as La2CuO4 are among the quantitatively best understood condensed-matter systems.

Spatially anisotropic Heisenberg models have been studied intensely due to their phenomenological importance as well as from the perspective of theoretical interest.5–8 For example, numerical evidence indicates that the anisotropic Heisenberg model with staggered arrangement of the antiferromagnetic couplings may belong to a new universality class, in contradiction to the $O(3)$ universality predictions.9 Further, it is argued that the Heisenberg model with spatially anisotropic couplings $J_1$ and $J_2$, as depicted in Fig. 1, is relevant to the newly discovered pinning effects of the electronic liquid crystal in the underdoped cuprate superconductor YBa2Cu3O6.45.10,11 It is observed that the YBa2Cu3O6.45 compound has a tiny in-plane lattice anisotropy which is strong enough to pin the orientation of the electronic liquid crystal in a particular direction. The authors of Ref. 12 demonstrated that the in-plane anisotropy of the spin stiffness of the Heisenberg model with spatially anisotropic couplings $J_1$ and $J_2$ can provide a possible mechanism for the pinning of the electronic liquid crystal direction in YBa2Cu3O6.45.

Since the anisotropy of the spin stiffness in the spin-$\frac{1}{2}$ Heisenberg model with different antiferromagnetic couplings $J_1$ and $J_2$ has not been studied in detail before with first-principles Monte Carlo methods, in this Brief Report we perform a Monte Carlo calculation to determine the low-energy constants, namely, the spin stiffnesses $\rho_{s1}$ and $\rho_{s2}$, staggered magnetization $M_s$, and spin wave velocity $c$. In particular, we investigate the $J_2/J_1$ dependence of $\rho_{s1}$ and $\rho_{s2}$, and find good agreement with earlier studies12 using series expansion methods in the weakly anisotropic regime. Our finding would lead to very strong pinning energy per Cu site in YBa2Cu3O6.45 as claimed in Ref. 12. However, deviations appear as one moves toward strong anisotropy. We argue that the deviations observed between our results and the naive expectation might indicate an unexpected behavior of the spin stiffness $\rho_s$ at extremely strong anisotropy.

II. MICROSCOPIC MODELS AND CORRESPONDING OBSERVABLES

The Heisenberg model we consider in this study is defined by the Hamilton operator

\begin{align*}
&J_2 \\
&J_1
\end{align*}

FIG. 1. The anisotropic Heisenberg model investigated in this study. $J_1$ and $J_2$ are the antiferromagnetic couplings in the 1- and 2-directions, respectively.
\[
H = \sum_{x} [J_1 \vec{S}_x \cdot \vec{S}_{x+1} + J_2 \vec{S}_x \cdot \vec{S}_{x+2}],
\]

where \( \vec{1} \) and \( \vec{2} \) refer to the two spatial unit vectors. Further, \( J_1 \) and \( J_2 \) in Eq. (1) are the antiferromagnetic couplings in the 1- and 2-directions, respectively. A physical quantity of central interest is the staggered susceptibility (corresponding to the third component of the staggered magnetization \( M^3 \)) that is given by

\[
\chi_s = \frac{1}{L_1 L_2} \int_0^\beta dt \frac{1}{Z} \text{Tr}[M^3(t)M^3(0)\exp(-\beta H)].
\]

Here \( \beta \) is the inverse temperature, \( L_1 \) and \( L_2 \) are the spatial box sizes in the one and two directions, respectively, and \( Z = \text{Tr} \exp(-\beta H) \) is the partition function. The staggered magnetization order parameter \( M_s \) is defined as \( M_s = \Sigma_x (-1)^{x_1+x_2} \vec{S}_x \). Another relevant quantity is the uniform susceptibility that is given by

\[
\chi_u = \frac{1}{L_1 L_2} \int_0^\beta dt \frac{1}{Z} \text{Tr}[M^3(t)M^3(0)\exp(-\beta H)].
\]

Here \( M = \Sigma_x \vec{S}_x \) is the uniform magnetization. Both \( \chi_s \) and \( \chi_u \) can be measured very efficiently with the loop-cluster algorithm using improved estimators. In particular, in the multicluster version of the algorithm the staggered susceptibility is given in terms of the cluster sizes \( C \) (which have the dimension of time), i.e., \( \chi_s = \frac{1}{M_C} \frac{1}{Z} \text{Tr}[\Sigma_i C_i^2] \). Similarly, the uniform susceptibility \( \chi_u = \frac{1}{L_1 L_2} \frac{1}{Z} \text{Tr}[\Sigma_i W_i(C)^2] \) is given in terms of the temporal winding number \( W_i = \Sigma_i W_i(C) \), which is the sum of winding numbers \( W_i \) of the loop clusters \( C \) around the Euclidean time direction. Similarly, the spatial winding numbers are defined by \( W_i = \Sigma_i W_i(C) \) with \( i \in \{1,2\} \).

### III. LOW-ENERGY EFFECTIVE THEORY FOR MAGNONS

Due to the spontaneous breaking of the SU(2) spin symmetry down to its U(1) subgroup, the low-energy physics of antiferromagnets is governed by two massless Goldstone bosons, the antiferromagnetic spin waves or magnons. The description of the low-energy magnon physics by an effective theory was pioneered by Chakravarty et al. A systematic low-energy effective field theory for magnons was further developed in Refs. 15–17. The staggered magnetization of an antiferromagnet is described by a unit-vector field \( \vec{e}(x) \) in the coset space \( SU(2)/U(1) = S^2 \), i.e., \( \vec{e}(x) = [e_1(x), e_2(x), e_3(x)] \) with \( \vec{e}(x)^2 = 1 \). Here \( x = (x_1, x_2, t) \) denotes a point in \( 2+1 \)-dimensional space-time. To leading order, the Euclidean magnon low-energy effective action takes the form

\[
S[\vec{e}] = \int_0^{L_1} dx_1 \int_0^{L_2} dx_2 \int_0^\beta dt \\left( \frac{\rho_1}{2} \partial_1 \vec{e} \cdot \partial_1 \vec{e} + \frac{\rho_2}{2} \partial_2 \vec{e} \cdot \partial_2 \vec{e} + \frac{\rho_3}{2c^2} \partial_3 \vec{e} \cdot \partial_3 \vec{e} \right),
\]

where the index \( i \in \{1,2\} \) labels the two spatial directions and \( t \) refers to the Euclidean time direction. The parameters \( \rho_1, \rho_2, \rho_3, \) and \( \rho_3 \) are the spin stiffness in the temporal and spatial directions, respectively, and \( c \) is the spin wave velocity. Rescaling \( x_1 = (\rho_2/\rho_1)^{1/3} x_1 \) and \( x_2 = (\rho_3/\rho_2)^{1/3} x_2 \), Eq. (4) can be rewritten as

\[
S[\vec{e}] = \int_0^{L_1} dx_1 \int_0^{L_2} dx_2 \int_0^\beta dt \frac{\rho_1}{2} \left( \partial_1 \vec{e} \cdot \partial_1 \vec{e} + \frac{c^2}{\rho_2} \partial_2 \vec{e} \cdot \partial_2 \vec{e} \right).
\]

Additionally requiring \( L_1^2 = L_2^2 = L \) we obey the condition of square area. Notice that the effective field theories described by Eqs. (4) and (5) are valid as long as the conditions \( L_i \beta \rho_i \gg 1 \) and \( L_i \beta \rho_i \gg 1 \) for \( i \in \{1,2\} \) hold, which is indeed the case for the setup of this study. Once these conditions are satisfied, the low-energy physics of the underlying microscopic model can be captured quantitatively by the effective field theory as demonstrated in Ref. 13. Further, in the so-called cubical regime (to be defined later), which is relevant to our study, the cutoff effects appear in the free-energy density only at next-to-next-to-next-to-leading order (NNNLO). The finite cutoff leads to higher-order terms in the effective Lagrangian due to the breaking of some symmetries and it introduces the cutoff dependence in the Fourier integrals (sums). By employing similar arguments as those presented in Ref. 18, one can show that higher-order corrections to Eq. (4) contain four derivatives and the leading cutoff effect in the Fourier integrals (sums) enters the free-energy density only at NNNLO. Therefore Eq. (5) is sufficient to derive up to next-to-next-to-leading order (NNLO) contributions to the observables considered here. We have further verified that the inclusion of NNNLO contributions to the relevant observables considered here lead to statistically consistent results with those not taking such corrections into account. Hence the volume and temperature dependences of \( \chi_s \) and \( \chi_u \) up to NNLO (to be presented below) are sufficient to describe our numerical data quantitatively, and the finite cutoff effects are negligible. Using above Euclidean action (5), detailed calculations of a variety of physical quantities including the NNLO contributions have been carried out in Ref. 18. Here we only quote the results that are relevant to our study, namely, the finite-temperature and finite-volume effects of the staggered susceptibility and the uniform susceptibility. The aspect ratio of a spatially quadratic space-time box with box size \( L \) is characterized by \( t = (\beta c / L)^{1/3} \), with which one distinguishes cubical space-time volumes with \( \beta c \ll L \) from cylindrical ones with \( \beta c \gg L \). In the cubical regime, the volume and temperature dependences of the staggered susceptibility are given by

\[
\chi_s = \frac{M_s^2 L^2}{3} \left[ 1 + \frac{2 \rho_1 L}{\rho_2 L} (\beta_s / l) \right]
\]

where \( M_s \) is the staggered magnetization density. Finally the uniform susceptibility takes the form

\[
033104-2
\]

\[
\chi_u = \frac{M_s^2 L^2}{3} \beta_s (l)
\]

\[
\left[ 1 + \frac{2 \rho_1 L}{\rho_2 L} (\beta_s / l) \right] + O \left( \frac{1}{L^3} \right)
\]

\[
\frac{c^2}{\rho_2} \partial_2 \vec{e} \cdot \partial_2 \vec{e} \right).
\]
In Eqs. (6) and (7), the functions $\beta_1(l), \tilde{\beta}_1(l)$, and $\phi(l)$, which only depend on $l$, are shape coefficients of the space-time box defined in Ref. 18.

IV. DETERMINATION OF THE LOW-ENERGY PARAMETERS AND DISCUSSIONS

In order to determine the low-energy constants for the anisotropic Heisenberg model given in Eq. (1), we have performed simulations within the range $0.05 \leq J_2/J_1 \leq 1.0$. The cubical regime is determined by the condition $\langle \Sigma_c W_2(C)^2 \rangle = \langle \Sigma_c W_1(C)^2 \rangle = \langle \Sigma_e W_1(C)^2 \rangle$ (which implies $\beta_c = 0$). Notice that since $J_2 \leq J_1$ in our simulations, one must increase the lattice size $L_1$ in order to fulfill the condition $\langle \Sigma_c W_2(C)^2 \rangle = \langle \Sigma_e W_2(C)^2 \rangle$ because Eqs. (6) and (7) are obtained for a $(2+1)$-dimensional box with equal extent in the two spatial directions. Therefore, an interpolation of the data points is required in order to be able to use Eqs. (6) and (7). Further, the low-energy parameters are extracted by fitting the Monte Carlo data to the effective field theory predictions. The quality of these fits is good as can be seen from Fig. 2 (the $\chi^2$/d.o.f. for all the fits is less than 1.25). Figure 3 shows $\rho_{11}$ and $\rho_{22}$ obtained from the fits, as functions of the ratio of the antiferromagnetic couplings, $J_2/J_1$. The values of $\rho_{11}(p_{22})$ obtained here agree quantitatively with those obtained using the series expansion in Ref. 12 at $J_2/J_1 = 0.8$ and 0.6 (0.8, 0.6, 0.4, and 0.2). At $J_2/J_1 = 0.4$, the value we obtained for $\rho_{11}$ is only slightly below the corresponding series expansion result in Ref. 12. However, sizable deviations begin to show up for stronger anisotropies. Further, we have not observed the saturation of $\rho_{11}$ to a one-dimensional (1D) limit, namely, $0.25J_1$ as suggested in Ref. 12, even at $J_2/J_1$ as small as 0.05. In particular, $\rho_{11}$ decreases slightly as one moves from $J_2/J_1 = 0.1$ to $J_2/J_1 = 0.05$ although they still agree within statistical errors. Of course, one cannot rule out that the anisotropies in $J_2/J_1$ considered here are still too far away from the regime where this particular Heisenberg model can be effectively described by its 1D limit. On the other hand, the Heisenberg model considered here and its 1D limit are two completely different systems because spontaneous symmetry breaking appears only in two dimension, still $\xi \approx \infty$ in both cases. Further, the low-temperature behavior of $\chi_a$ in the 1D system is known to be completely different from that of the two-dimensional system.\cite{18,19} Although intuitively one might expect a continuous transition of $\rho_{11}$, one cannot rule out an unexpected behavior of $\rho_{11}$ as one moves from this Heisenberg model toward its 1D limit. In particular, since earlier studies indicate that long-range order already sets in even for infinitesimally small $J_2/J_1$,\cite{5,20,21} it would be interesting to investigate the critical properties of this system by means of renormalization group techniques.\cite{22,23}

FIG. 2. (Color online) Comparison between our numerical results (data points) and the theoretical predictions (solid lines) that are obtained by using the low-energy parameters from the fits.

\[ \chi_a = \frac{2\rho_2}{3c} \left[ 1 + \frac{c}{3\rho_{LL}} \beta_1(l) + \frac{1}{3\rho_{LL}} \beta_2(l) \right]^2 \times \left[ \beta_2(l) - 1 + \frac{1}{3\rho_{LL}} \beta_3(l) \right] + O \left( \frac{1}{L^3} \right). \] (7)
Next, we would like to turn to discussing the relevance of our results to the pinning effect observed empirically in YBa$_2$Cu$_3$O$_{6.45}$. In Ref. 12 it is argued that the $J_2/J_1$ dependence of the spin stiffnesses in the spatially anisotropic Heisenberg model studied in this work would lead to a very strong pinning energy per Cu site (one order of magnitude larger compared to the corresponding pinning energy in La$_2$CuO$_4$). To be more precise, it is the quantity $\kappa$ that is defined by $\rho_2/\rho_1=1+\kappa(J_2/J_1-1)$ in the weak anisotropy regime that results in the claim made in Ref. 12. Since the spin stiffnesses calculated here agree with those obtained by series expansion in the weak anisotropy regime, which in turn implies that our $\kappa$ agrees with that in Ref. 12, we conclude that the pinning energy per Cu site is indeed very strong. Hence the in-plane anisotropy of the spin stiffness of the Heisenberg model with anisotropic couplings $J_1$ and $J_2$ can indeed provide a possible mechanism for the pinning of the electronic liquid crystal direction in YBa$_2$Cu$_3$O$_{6.45}$.

V. CONCLUSIONS

In this note, we have numerically studied the Heisenberg model with anisotropic couplings $J_1$ and $J_2$ using a loop cluster algorithm. The corresponding low-energy constants are determined with high precision. Further, the $J_2/J_1$ dependence of $\rho_{11}$ and $\rho_{12}$ is investigated in detail and our results agree quantitatively with those obtained by series expansion in the weakly anisotropic regime. On the other hand, we observe discrepancies between our results and series expansion results in the strongly anisotropic regime. However, the results of our study still lead to very strong pinning energy per Cu site in YBa$_2$Cu$_3$O$_{6.45}$, which agrees with the claim made by the authors in Ref. 12. Finally we find that an unexpected behavior of $\rho_{11}$ might be observed as one approaches much stronger anisotropy regime than those considered in this study.

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*B. Jiang@itp.unibe.ch