Phase diagram of a Heisenberg spin-Peierls model with quantum phonons

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Using a new version of the density-matrix renormalization group we determine the phase diagram of a model of an antiferromagnetic Heisenberg spin chain where the spins interact with quantum phonons. A quantum phase transition from a gapless spin-fluid state to a gapped dimerized phase occurs at a non-zero value of the spin-phonon coupling. The transition is in the same universality class as that of a frustrated spin chain, to which the model maps in the anti-adiabatic limit. We argue that realistic modeling of known spin-Peierls materials should include the effects of quantum phonons.

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Challenged by the discovery of high-temperature superconductivity in doped antiferromagnets, our understanding of quantum magnetism in low dimensions has increased significantly over the past decade. However, the effect of the interaction of quantum spin systems with further degrees of freedom such as disorder, phonons, and holes produced by doping is still poorly understood. Interest in models of spins interacting with phonons has increased significantly since the discovery of a spin-Peierls transition in the inorganic compound CuGeO$_3$. The availability of large, high-quality single crystals has led to much more extensive experimental studies than on the organic spin-Peierls materials studied in the 1970’s.

The fact that a spin-1/2 antiferromagnetic Heisenberg chain is unstable to a static uniform dimerization is known as the spin-Peierls instability. This occurs because dimerization opens a gap $\Delta$ in the spin excitation spectrum and lowers the total magnetic energy at a greater rate than the increase in elastic energy due to the dimerization. Until very recently almost all theoretical treatments have used this static picture which we can only expect to be valid in the adiabatic regime where typical frequencies $\omega$ of the phonons associated with the dimerization are much smaller than the magnetic energy scales such as $\Delta$ and the antiferromagnetic exchange integral $J$.

It has recently been pointed out that CuGeO$_3$ is not in this adiabatic regime, stimulating several numerical studies with dynamical phonons.

In this Letter we study a model of a spin-1/2 antiferromagnetic Heisenberg chain interacting with quantum phonons using a powerful new numerical technique that allows an essentially exact treatment of both the spins and the phonons at a fully quantum-mechanical level. Our main result is the phase diagram in Fig. 1 in which the adiabaticity parameter $J/\omega$ varies over several decades. We find that the spin-phonon coupling must be larger than some non-zero critical value for the spin-Peierls instability to occur. This is in contrast to the static case ($\omega/J \to 0$) for which dimerization occurs for any value of the coupling. Hence, quantum lattice fluctuations can destroy Heisenberg spin-Peierls order. We find that the quantum phase transition from the spin-fluid state to the gapped state is in the same universality class as the dimerization transition of the $J_1$-$J_2$ frustrated spin chain. Our results have important implications for the modeling of spin-Peierls materials.

The model we study is one of the simplest possible. It consists of a local phonon on each site and the antiferromagnetic exchange on neighbouring sites varies linearly with the difference between the phonon amplitudes on the two sites. The Hamiltonian is

$$H = \sum_{i=1}^{N} \left( J + g \left( b_{i+1} + b_{i+1}^\dagger - b_{i} - b_{i}^\dagger \right) \right) \vec{S}_i \cdot \vec{S}_{i+1} + \omega \sum_{i=1}^{N} b_{i}^\dagger b_{i}. $$

(1)

Here $\vec{S}_i$ is the $S = 1/2$ spin operator on site $i$ and $b_i$ destroys a phonon of frequency $\omega$ on site $i$. We assume a periodic chain of $N$ sites.

Insight into this model can be obtained by considering the anti-adiabatic limit ($\omega >> J$). One can then integrate out the phonon degrees of freedom to obtain the following effective Hamiltonian for the spin degrees of freedom:

$$H_{\text{eff}} = J_1 \sum_{i=1}^{N} \vec{S}_i \cdot \vec{S}_{i+1} + J_2 \sum_{i=1}^{N} \vec{S}_i \cdot \vec{S}_{i+2} $$(2)

where $J_1 = J + g^2/\omega$ and $J_2 = g^2/2\omega$. Uhrig recently obtained the same Hamiltonian, calculating $J_1$ and $J_2$ to next order in $J/\omega$.

$$J_1 = J + g^2/\omega - 3g^2J/2\omega^2 + \ldots$$

$$J_2 = g^2/2\omega + 3g^2J/2\omega^2 + \ldots$$

(3)

(4)

The frustrated spin chain Eqn. (3) or $J_1$-$J_2$ model has been extensively studied and is well understood. If $\alpha$ =
$J_2/J_1$ then at a critical value of $\alpha = \alpha_c = 0.241167(5)$ the model undergoes a quantum phase transition from a gapless spin-fluid state with quasi-long-range antiferromagnetic order to a gapped phase with long-range dimer order $1^{12}$. Uhrig pointed out that this implies that in the anti-adiabatic regime $1^{12}$ possesses a non-zero critical coupling $g_c$. To second order in $J/\omega$, 
\[ g_c^2/\omega = \frac{\alpha_c J}{2} - \alpha_c + 3(1 + \alpha_c)J/2\omega. \quad (5) \]
We have confirmed this result numerically (see Fig. 1). Furthermore, this non-zero critical coupling $g_c$ still occurs well into the adiabatic regime. It is interesting that although $1^{12}$ is only valid to second order in $J/\omega$ it gives a good description of $g_c$ up to $J/\omega \sim 1$.

Models such as $1^{12}$, which involve bosons are a challenge to study numerically due to the large number of degrees of freedom per site. The density matrix renormalization group (DMRG) method $13$ has the potential for obtaining definitive results for these models by studying very large systems. Several schemes based on the DMRG have recently been developed to treat models involving phonons $4^{14}$. We employ a new “four-block” DMRG method $14$ which allows us to treat the phonons and spins on an equal footing and to study systems as large as 256 sites. This is in contrast to some recent exact diagonalization studies of spin-phonon models that were limited to small systems and/or used uncontrolled truncations of the phonon degrees of freedom $3^{14}$. We previously used this method to obtain the phase diagram of the Holstein model with spinless fermions $17$.

The four-block method can be used to calculate the ground state energy $E_0$ and the singlet and triplet gaps $\Delta_s$ and $\Delta_{st}$ for periodic systems $13$. Table I shows the DMRG convergence of the gaps with the single truncation parameter $\epsilon$ $18$ for a representative parameter set. It can be seen that the gaps are sufficiently well resolved to be useful for finite-size scaling analyses. The error of around 0.1% in the $N = 128$ site system is typical of the error in the largest systems studied for a given set of parameters.

We determine the critical coupling using the gap-crossing method used by Okamoto and Nomura $12$ to determine the critical coupling $\alpha_c$ in the frustrated Heisenberg model $2$. The convergence of the crossover coupling $\alpha_c(N)$ with $N$ is rapid due to the absence of logarithmic corrections at the critical point $11,12$. If the system is gapless with quasi-long-range Néel order for $0 \leq g \leq g_c$, the lowest excitation is the triplet state, i.e. $\Delta_{st} < \Delta_s$ (for sufficiently large $N$) and $\Delta_{st}, \Delta_s \to 0$ as $N \to \infty$. If for $g > g_c$ the system has a non-zero gap $\Delta$ and is dimerised with a doubly degenerate ground state, then the first excited singlet state becomes degenerate with the ground state in the bulk limit $19$. That is, $\Delta_s < \Delta_{st}$ (for sufficiently large $N$), $\Delta_s \to 0$, and $\Delta_{st} \to \Delta > 0$ as $N \to \infty$. A finite lattice crossover coupling $g_c(N)$ is defined by $\Delta_{st} = \Delta_s$. As shown in Table I, $g_c(N)$ rapidly approaches a limit as $N \to \infty$. This limit is the critical coupling $g_c$ separating gapless and gapped phases. For the $J/\omega > 1$ cases, where the $N$ dependence is substantial, $g_c(N)$ is well described by the functional form $g_c(N) \sim g_c - A \exp(-BN)$ and non-linear fitting is used to determine $g_c$ $24$. The resulting phase boundary is plotted in Fig. 1. The DMRG, discretization and fitting errors in $g_c$ are estimated to be no greater than a few percent.

From conformal invariance the finite-size energies of the spin-fluid should satisfy $12$: 
\[ E_0 \sim N\epsilon_\infty + \frac{\pi v_0}{6N} + \ldots, \quad (6) \]
\[ \frac{1}{4}(3\Delta_{st} + \Delta_s) \sim \frac{\pi v_1}{N}(1 + \ldots), \quad (7) \]
where $\epsilon_\infty$ is the bulk ground state energy density and $v_0 = v_1 = v_\sigma$ is the spin wave velocity. The combination of the gaps in Eqn. (5) is chosen to cancel the logarithmic corrections.

We have performed a number of consistency checks on our results. First, in Fig. 2, $v_\sigma$ as determined by $12$ is plotted as a function of $g$ for a phonon frequency deep into the anti-adiabatic regime ($J/\omega = 0.005$), together with the same quantity determined from the corresponding $J_1$-$J_2$ model. The results from the two approaches agree well. This confirms the mapping between the two models in the anti-adiabatic regime. Second, we note that the DMRG results for the phase boundary agree well with the result $12$ from the mapping in the anti-adiabatic limit (See the dotted line in Fig. 1). Third, for general phonon frequencies, we calculate the ratio $v_0/v_1$ which should equal unity. At $g = g_c$ it is one within errors expected from corrections to scaling and DMRG truncation, over the range of frequencies studied. Values vary from 0.98 ± 0.04 for $J/\omega = 0.005$ to 1.07 ± 0.10 for $J/\omega = 10$.

For a K-T transition, the gap $\Delta = \lim_{N \to \infty} \Delta_{st}$ is expected to have an essential singularity at $g = g_c$. In Fig. 3, $\Delta_{st}$ is plotted as a function of $g$ for various $N$ in a case of intermediate coupling $J/\omega = 1$. Two-point linear extrapolations (in $1/N$) to $N = \infty$ are included in the plot. These estimates of $\Delta$ are shown to be well fitted by the K-T form $12$ $\Delta \sim A f(g) \exp(-B f(g)^2)$ where $f(g) \equiv (g - g_c)^{-1/2}$. Note that the gap crossover method (Table I) is substantially more accurate than this fitting procedure for determining $g_c$, the latter tending to overestimate $g_c$ $16$.

In the adiabatic regime ($\omega << J$) there is strong mixing between spin singlet and phonon excitations. An analogous effect was observed for the Holstein model $17$. In the case of $12$ this is manifest in nonlinear corrections to the scaling of $\Delta_s$. That is, $\Delta_s$ is found to be phonon like (flat in $1/N$) until the characteristic spin energy
$2\pi J/N$ decreases below the bare phonon frequency $\omega$, at which point $\Delta_\omega$ begins to vanish, as $1/N$ ($0 \leq g \leq g_c$), or exponentially ($g > g_c$). This can be seen in Table I from the slow convergence of $g_c(N)$ with $N$ for the $J/\omega = 10$ case.

Next, we consider the validity of the static approximation in the adiabatic regime, where the phonon operators $b_i$ in (1) are replaced by the constant dimerization $(-1)^i\delta$, the total energy is minimized as a function of $\delta$ then the gap is calculated for this optimal value of $\delta$. This calculation was performed by using the four-block DMRG method to solve for the ground state energy and gap in the dimerised Heisenberg model [22]. The resulting adiabatic curve is compared in Fig. 3 to the extrapolated gap

driven by the model to the frustrated spin chain (2) in the antiferromagnetic chain (2). Quantum phonon fluctuations are important in known spin-Peierls materials.

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TABLE I. Four-block DMRG convergence of the singlet and triplet gaps $\Delta_{ss}$ and $\Delta_{st}$ of the spin-Peierls model (1) with the truncation parameter $\epsilon$ for various periodic lattices of size $N$, where $J/\omega = 1$ and $g/\omega = 0.4$. 

| $N$ | $\epsilon$ | $\Delta_{ss}/\omega$ | $\Delta_{st}/\omega$ |
|-----|-------------|------------------------|------------------------|
| 8   | $10^{-16}$  | 0.31374961              | 0.5183251              |
| 8   | $10^{-20}$  | 0.31372889              | 0.5183254              |
| 8   | $10^{-22}$  | 0.31372870              | 0.5183254              |
| 32  | $10^{-13}$  | 0.0764782               | 0.133925               |
| 32  | $10^{-15}$  | 0.0765958               | 0.133785               |
| 32  | $10^{-16}$  | 0.0765933               | 0.133778               |
| 128 | $10^{-10}$  | 0.014909                | 0.04009                |
| 128 | $10^{-11}$  | 0.014817                | 0.03856                |
| 128 | $10^{-13}$  | 0.014619                | 0.03790                |
| 128 | $10^{-14}$  | 0.014648                | 0.03775                |

TABLE II. Convergence of the crossover coupling $g_c(N)/\omega$ with lattice size $N$ for various values of the adiabaticity parameter $J/\omega$. $g_c(N)$ is defined by $\Delta_{ss} = \Delta_{st}$ and converges to the critical coupling $g_c$ as $N \to \infty$. 

| $N$ | 0.005 | 0.1  | 1.0  | 2.0  | 10.0 |
|-----|-------|------|------|------|------|
| 4   | 0.0692| 0.237| 0.120| —    | —    |
| 8   | 0.0681| 0.228| 0.273| 0.092| —    |
| 16  | 0.0671| 0.225| 0.302| 0.274| —    |
| 32  | —     | 0.223| 0.308| 0.310| —    |
| 64  | —     | —    | 0.309| 0.318| 0.249|
| 128 | —     | —    | —    | 0.318| —    |
| 256 | —     | —    | —    | —    | 0.339|

FIG. 1. Zero temperature phase diagram of the spin-Peierls antiferromagnetic chain of spins interacting with quantum phonons (Eqn. (1)). For small spin-phonon coupling $g$ the system is a gapless spin-fluid. For large $g$ the system is dimerized and has an energy gap. The diamonds with error bars denote the phase boundary from this DMRG study. The dotted line is (Eqn. (5)) the phase boundary which results from an approximate mapping onto the $J_1$-$J_2$ model (frustrated antiferromagnetic chain, Eqn. (3)) which becomes exact in the anti-adiabatic limit $J/\omega \to 0$.

FIG. 2. The spin wave velocity $v_s$ as a function of the electron-phonon coupling $g$ for a large phonon frequency $J/\omega = 0.005$ (anti-adiabatic regime). DMRG results (from extrapolating the $N = 16$ and 32 data using (1)) are indicated by diamonds. The triangles are obtained by solving the $N = 16$ and 32 site $J_1$-$J_2$ model (Eqn. (3)), with $J_1$ and $J_2$ given by (4) and (5). The dotted line arises from applying an approximate result for $v_s$ (30) to the same $J_1$-$J_2$ model.
FIG. 3. The singlet-triplet gap $\Delta_{st}$ of the spin-Peierls model as a function of the coupling $g$ for various lattice sizes $N$ for an intermediate phonon frequency $J/\omega = 1$. Extrapolations (in $1/N$, using the two largest values of $N$) to $N = \infty$ are given by the solid diamonds. These are fitted to the K-T form $A f(g) \exp(-B f(g)^2)$, where $f(g) \equiv (g - g_c)^{-1/2}$ (solid line). The critical coupling $g_c$ is not obtained from this fit. It is substantially more accurate to use the gap crossover method (see Table I). The inset shows the extrapolated gap (using $N = 32$ and 64) for a small phonon frequency (adiabatic regime) $J/\omega = 10$. The dashed line is the result for the static limit where the quantum phonon fluctuations are neglected [22].