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Tensor renormalization group: Local magnetizations, correlation functions, and phase diagrams of systems with quenched randomness

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The tensor renormalization-group method, developed by Levin and Nave, brings systematic improovability to the position-space renormalization-group method and yields essentially exact results for phase diagrams and entire thermodynamic functions. The method, previously used on systems with no quenched randomness, is extended in this study to systems with quenched randomness. Local magnetizations and correlation functions as a function of spin separation are calculated as tensor products subject to renormalization-group transformation. Phase diagrams are extracted from the long-distance behavior of the correlation functions. The approach is illustrated with the quenched bond-diluted Ising model on the triangular lattice. An accurate phase diagram is obtained in temperature and bond-dilution probability for the entire temperature range down to the percolation threshold at zero temperature.

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I. INTRODUCTION

The tensor renormalization-group (TRG) method developed by Levin and Nave [1] is a highly useful update of the traditional position-space renormalization-group approaches. While these founding approaches relied on uncontrolled approximations that were often system specific [2–7], the TRG is general in scope—it works on any classical two-dimensional lattice Hamiltonian with local interactions—and its accuracy can be systematically improved to converge on the exact thermodynamic results. Along with these advantages, the method fits within the conceptual framework of traditional renormalization-group theory: it is a mapping between Hamiltonians on the original and coarse-grained lattices, and phase-transition behavior can be extracted from flows of the Hamiltonians as the transformation is iterated [8].

The initial TRG study demonstrated the power of the approach in the context of the triangular-lattice Ising model [1]. Since then it has proven a versatile tool for a variety of classical systems, including the frustrated Ising model on a Shastry-Sutherland lattice [9], relevant to magnetization plateaus in rare-earth tetraborides, and the zero-hopping limit of a model for ultracold bosonic polar molecules on a hexagonal optical lattice [10]. Moreover, the ideas behind the TRG method have become the kernel for developments in two-dimensional quantum systems [11–16], most notably tensor-entanglement renormalization group for studying symmetry breaking and topological phase transitions [11] and accurate methods to calculate ground-state expectation values [12–14]. Beyond the precision of the method, a key factor spurring the growth of TRG applications in both classical and quantum cases is computational efficiency: the CPU cost of carrying out TRG scales linearly with lattice size [14].

Given these promising characteristics, TRG is a natural candidate for tackling models with quenched randomness—a field where extracting accurate phase diagram information is a significant challenge. The current study presents the example of TRG applied to such a system with frozen disorder, namely, the percolative system of the bond-diluted triangular-lattice Ising ferromagnet, yielding, as seen in Fig. 1, a highly accurate global phase diagram down to zero temperature, where it connects with the percolation transition.

FIG. 1. (Color online) The phase diagram of the bond-diluted Ising model on a triangular lattice, showing the transition temperature as a function of the bond dilution probability p. The ferromagnetic (Ferro) and paramagnetic (Para) phases are marked. The phase boundary line between these two phases connects, at zero temperature, with the percolation transition on the triangular lattice. Filled circles are our results using the TRG method with (D=12) together with finite-size scaling, as described in Sec. IV. The red dotted line is the result of the work of Georges et al. [17], which is exact on the scale of the figure.
Although the tensor can have as many as \( N^2 = 8 \times 3^3 \) sites and \( K = 4 \times 3^{n+1} \) bonds. The TRG method involves a renormalization-group transformation that reverses this construction process, mapping the system at step \( n \) to one at step \( n-1 \).

The hexagonal lattice of any size can be decomposed into two sublattices \( A \) and \( B \), such that the nearest neighbors of one type belong to the other type. As an example, we label the sublattices in the \( n=0 \) panel of Fig. 2. We distinguish the sublattice tensors with superscripts, \( T^A_{ijk} \) or \( T^B_{ijk} \). In the partition function sum of Eq. (1), each bond index \( i_m \) appears twice, once within an \( A \) tensor and once within the neighboring \( B \) tensor linked through that bond. Thus, evaluating \( Z \) consists of performing \( K \) tensor contractions.

In addition to the bond variables, the general system we consider has quenched random degrees of freedom, though for notational simplicity we shall not explicitly show the dependence of \( T \) on these. Physical observables \( Q \) will be expressed as \( \langle Q \rangle \), where \( \langle \cdot \rangle \) denotes the thermodynamic average over the bond degrees of freedom and \( \langle \cdot \rangle \) denotes the configurational average over the quenched disorder.

### B. TRG transformation

The TRG transformation consists of two steps known as rewiring and decimation. In the rewiring step, the bonds of every pair of neighboring tensors \( T^A \) and \( T^B \) are reconnected, rewriting them as a contraction of two new tensors \( S^A \) and \( S^B \). The reconnection pattern is illustrated in Figs. 3(a) and 3(b) and can be broken down into three basic cases (highlighted in different colors) involving different orientations of the initial \( T^A \) and \( T^B \) tensors. In our graphical convention, the vertex where three solid lines meet is a \( T \) tensor and the vertex where three dashed lines meet is an \( S \) tensor. Indices on a tensor, i.e., \( T^A_{ij} \), correspond to bonds labeled \( i, j \), and \( k \) arranged counterclockwise around the tensor, with the first index marking the vertical bond for the \( T \) tensors and the horizontal bond for the \( S \) tensors. Thus, for example, the three rewirings shown in Fig. 3(b) denote the mathematical identities,

\[
Z = \sum_{i_1 \ldots i_d} T_{i_1 j_1} T_{j_1 k_1} \cdots \cdots T_{K-2 k_{K-1} i_{K-1} i_{K}} \tag{1}
\]

where, for each of the \( N \) sites in the hexagonal lattice, a real-valued tensor \( T_{i_1 j_1 k} \) is a Boltzmann weight, depending on the configuration of the three bonds meeting at the site. The bond degrees of freedom correspond to each tensor index running from 1 to \( d \). These bond indices are labeled \( i_1 \) through \( i_d \) for the total of \( K = 3N/2 \) bonds in the lattice. Although the tensor can have as many as \( d^2 \) distinct nonzero elements, in practice some bond configurations may be disallowed for a given Hamiltonian, corresponding to zero-valued tensor elements.

To facilitate the description of the TRG procedure, the hexagonal lattice is constructed as illustrated in Fig. 2: at the \( n \)th step, we replace each vertex with a hexagon, with the initial structure denoted \( n=0 \). We impose periodic boundary conditions, such that the top and bottom edges are equivalent, as well as the left and right edges, so that the lattice effectively lies on the surface of a torus. After the \( n \)th step, the system has \( N = 8 \times 3^3 \) sites and \( K = 4 \times 3^{n+1} \) bonds.
This problem is related to a general feature of position-space renormalization on lattices: except for specially tailored geometries (i.e., hierarchical lattices \([18-20]\)), the number of couplings in the renormalized Hamiltonian grows with each coarse graining. For the TRG, we can tackle this issue in a systematic fashion by truncating the index range with an upper bound \(D\). In Eq. (3) for \(T^A\) and \(T^B\), we shall allow the indices \(\nu, \gamma, \text{ and } \delta\) to run only up to \(\bar{d} = \min(d^2, D)\). This is equivalent to using truncated matrices \(\bar{S}^A\) and \(\bar{S}^B\) in the rewiring step, where \(\bar{S}^A\) is the first \(\bar{d}\) columns of the \(d^2 \times d^2\) matrix \(S^A\) and \(\bar{S}^B\) is the first \(\bar{d}\) columns of \(S^B\). As a result, the rewiring becomes approximate, \(M = \bar{S}^A(\bar{S}^B)^T\). However, since the first \(\bar{d}\) columns correspond to the largest singular values, the approximation is relatively accurate even for small \(D\) and rapidly converges as \(D\) is increased [1,8]. With this cutoff, the maximum size of the tensors is bounded as the TRG procedure is iterated, and we can extract numerically thermodynamic information from flows within a finite-dimensional space of real-valued tensor elements.

III. TRG FOR QUENCHED RANDOMNESS: BOND-DILUTED ISING MODEL

A. Bond-diluted Ising Hamiltonian and its mapping onto a tensor network

The general Hamiltonian for a quenched random Ising system is

\[-\beta H = \sum_{\langle ij \rangle} (J_{ij} s_i s_j + H_{ij}(s_i + s_j)), \quad s_i = \pm 1,\]  

where \(\beta = 1/k_b T\), \(J_{ij}\) and \(H_{ij}\) are, respectively, the local spin-spin coupling and magnetic field for sites \(i\) and \(j\), and \(\langle ij \rangle\) denotes a sum over nearest-neighbor pairs of sites. Although this Hamiltonian encompasses a variety of models, all the way to the random-field spin glass [21], we shall here focus on a the bond-diluted Ising case, where the interaction constants \(J_{ij}\) are distributed with a quenched probability \(P(J_{ij})\) of the form.

FIG. 3. (Color) The TRG transformation described in Sec. II B. (a) The hexagonal tensor network, with the three representative orientations of \(T^A\) and \(T^B\) tensor pairs, labeled as cases 1–3 and highlighted in different colors. (b) For each of the three cases, the rewiring step [Eq. (2)] expressing the contraction equivalently in terms of different tensors \(S^A\) and \(S^B\). (c) After every pair of tensors is rewired, the resulting martini lattice of \(S^A\) and \(S^B\) tensors. The original lattice is superimposed in gray for reference. (d) The decimation step [Eq. (3)], which replaces three \(S^A\) tensors by a renormalized \(T^A\) tensor (and analogously for \(S^B\)). (e) The final lattice of renormalized \(T^A\) and \(T^B\) tensors, with the original lattice in gray for comparison.
FIG. 4. (Color online) Duality mapping between spin states on the triangular lattice and bond variables in the tensor network. The variables $s_i = \pm 1$ at the triangle corners correspond to Ising spins in the Hamiltonian of Eq. (4). The bond variables $\sigma_i$ are products of the $s_i$ connected by the bond. Up and down triangles yield type A and B tensors, respectively.

$$\mathcal{P}(J_{ij}) = p \delta(J_{ij}) + (1 - p) \delta(J_{ij} - J).$$

Here, $J > 0$, implying ferromagnetism and $p$ is the fraction of missing bonds. While we restrict our attention to the zero magnetic-field subspace, $H_{ij} = 0$, formally the local fields will be kept in the Hamiltonian in order to take derivatives to obtain thermodynamic functions.

Starting with the Hamiltonian of Eq. (4) on a triangular lattice, a duality transformation allows us to express the partition function as a hexagonal-lattice tensor network. (The duality for Potts spins would generate three-point interactions, which would be included in the definition of the tensor $T_{i_1i_2i_3}$.) Each triangle in the triangular lattice corresponds to a tensor, with up triangles associated with a $T^A$ and down triangles with a $T^B$, as shown in Fig. 4. For spin variables $s_i$, $s_j$, and $s_k$ in a given triangle in the manner illustrated in the figure, we define corresponding edge variables $\sigma_m$ as the products of neighboring $s_k$; i.e., for the type A triangle, $\sigma_1 = s_k s_1$, $\sigma_2 = s_k s_2$, and $\sigma_3 = s_k s_3$ and for the type B triangle, $\sigma_1 = s_k s_1$, $\sigma_2 = s_k s_2$, and $\sigma_3 = s_k s_3$. Since $s_k = \pm 1$ and $\sigma_m = \pm 1$, we can now introduce a composite index $m = (5 - \sigma_m - 2s_m)/2$ which runs from 1 to 4 and describes the four possible states of the $m$th triangle edge. Letting $J_{ij}$ be the coupling $J_{ij}$ associated with this edge and $H_m = H_{ij}$ be the edge magnetic field, then the tensors for the two triangles are

$$T^A_{i_1i_2i_3} = \exp \left[ \frac{1}{2} \sum_{m=1}^{3} J_m \sigma_m + H_m (1 + \sigma_m) s_m \right] \times P(\sigma_1 \sigma_2 \sigma_3) \cdot P(\sigma_1 s_1 s_3) P(\sigma_2 s_2 s_1) P(\sigma_3 s_3 s_2),$$

$$T^B_{i_1i_2i_3} = \exp \left[ \frac{1}{2} \sum_{m=1}^{3} J_m \sigma_m + H_m (1 + \sigma_m) s_m \right] \times P(\sigma_1 \sigma_2 \sigma_3) \cdot P(\sigma_1 s_1 s_3) P(\sigma_2 s_2 s_1) P(\sigma_3 s_3 s_2),$$

where $P(x) = (1 + x)/2$ is a projection operator. The $P$ factors in the tensors remove the bond states that do not correspond to a physically allowable spin configuration. As a result of the projection operators, only 8 out of the 64 elements in the tensor are nonzero. These are listed, for the first renormalization step, in the third and sixth columns of Table I for $T^A$ and $T^B$, respectively.

### B. Local magnetization and spin-spin correlation function

In order to derive expressions for thermodynamic quantities in the tensor formalism, let us now restrict the notation $T^A$ and $T^B$ to tensors in the zero magnetic-field subspace. We place a local magnetic field $H_i$ only at a single location $i$. Let us call the two tensors which share this bond $\tilde{T}^A$ and $\tilde{T}^B$. These are the only two tensors in the system whose components are modified by the local field. The corresponding partition function is

$$Z_i = \sum_{i_1, \ldots, i_k} T^A_{i_1i_2i_3} T^B_{i_4i_5i_6} \cdots \tilde{T}^A_{i_ki_{k+1}} \tilde{T}^B_{i_{k+2}i_{k+3}} \cdots.$$

Without loss of generality we take the contraction of the $\tilde{T}^A$ and $\tilde{T}^B$ tensors to be case 2 in Eq. (2) since the derivation proceeds analogously for the other cases.

### Table I. The tensor elements for the bond-diluted Ising model, as defined in Secs. III A and III B, for the first renormalization step. The first triangle gives the spin state $(s_1, s_2, s_3)$ for a triangle of the original triangular lattice, following the convention of Fig. 4. For the type A triangle, the next three columns show the associated composite indices $(i_1, i_2, i_3)$ and the tensor elements $T^A_{i_1i_2i_3}$ and $D^A_{i_1i_2i_3}$. The last three columns show the analogous information for the type B triangle. All tensor elements not shown are zero.

<table>
<thead>
<tr>
<th>Spin state $(s_1, s_2, s_3)$</th>
<th>Type A $T^A_{i_1i_2i_3}$</th>
<th>Type B $T^B_{i_1i_2i_3}$</th>
<th>$D^A_{i_1i_2i_3}$</th>
<th>$D^B_{i_1i_2i_3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 1, 1)</td>
<td>111</td>
<td>111</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
</tr>
<tr>
<td>(1, 1, 2)</td>
<td>124</td>
<td>124</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(1, 2, 1)</td>
<td>142</td>
<td>142</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
</tr>
<tr>
<td>(2, 1, 1)</td>
<td>243</td>
<td>243</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(1, 2, 2)</td>
<td>421</td>
<td>421</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(2, 1, 2)</td>
<td>324</td>
<td>324</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
</tr>
<tr>
<td>(2, 2, 1)</td>
<td>324</td>
<td>324</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(2, 2, 2)</td>
<td>333</td>
<td>333</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
<td>$e^{(1/2)(J_{12}+J_{13}+J_{23})}$</td>
</tr>
</tbody>
</table>
A similar derivation for the correlation function yields

\[
T\text{ENSOR RENORMALIZATION GROUP: LOCAL...}
\]

\[
\text{Table I.}
\]

\[
\text{renormalization step, in the fourth and seventh columns of}
\]

\[
\text{second terms in the brackets on the right-hand side of Eq.}
\]

\[
\text{/H}_{20849}
\]

\[
\text{cator of thermodynamic phase behavior. In this case, the four}
\]

\[
\text{sites}
\]

\[
\text{The nonzero elements of}
\]

\[
\text{shown.}
\]

\[
\text{method for bond dilution probability}
\]

\[
p=0.1\text{ and cutoff parameter}
\]

\[
D=8\text{. The curves for four different initial tensor network sizes}
\]

\[
N\text{ are shown.}
\]

\[
\text{The local magnetization is}
\]

\[
m_{k} = \langle s_{i} s_{j} /2 \rangle = \langle S_{k} \rangle
\]

\[
\text{for the sites}
\]

\[
i \text{ and}
\]

\[
j \text{ associated with the bond}
\]

\[
k\text{. In terms of the local}
\]

\[
magnetic field}
\]

\[
H_{k}\text{, the magnetization}
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\[
m_{k}
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\[
\text{is given by the deriv}
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\[
\text{ative}
\]

\[
m_{k} = \frac{1}{2} \frac{\partial \ln Z}{\partial H_{k}}\mid_{H_{k}=0}
\]

\[
= \frac{1}{2Z} \sum_{i, j, \ldots, K} \{ T_{ij}^{A} T_{ij}^{B} \cdots D_{ij}^{A} T_{ij}^{B} \cdots 
\]

\[
+ T_{ij}^{A} T_{ij}^{B} \cdots D_{ij}^{B} T_{ij}^{B} \cdots \},
\]

\[
\text{where the differentiated tensors are}
\]

\[
D_{ij}^{A} = \frac{\partial T_{ij}^{A}}{\partial H_{k}}\bigg|_{H_{k}=0}, \quad D_{ij}^{B} = \frac{\partial T_{ij}^{B}}{\partial H_{k}}\bigg|_{H_{k}=0}
\]

\[
\text{The nonzero elements of}
\]

\[
D^{A}\text{ and}
\]

\[
D^{B}
\]

\[
\text{are shown, for the first}
\]

\[
\text{renormalization step, in the fourth and seventh columns of}
\]

\[
\text{Table I.}
\]

\[
\text{After taking the average over the disorder, the first and}
\]

\[
\text{second terms in the brackets on the right-hand side of Eq.}
\]

\[
\text{(8) are equivalent, so that}
\]

\[
[m_{k}] = [\langle S_{k} \rangle] = \left[ Z^{-1} \sum_{i, j, \ldots, K} T_{ij}^{A} T_{ij}^{B} \cdots D_{ij}^{A} T_{ij}^{B} \cdots \right].
\]

\[
\text{A similar derivation for the correlation function yields}
\]

\[
[\langle S_{k} S_{j} \rangle] = \left[ Z^{-1} \sum_{i, j, \ldots, K} T_{ij}^{A} T_{ij}^{B} \cdots D_{ij}^{A} T_{ij}^{B} \cdots \right].
\]

\[
\text{We shall be interested in long-range correlations as an indi}
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\[
cator of thermodynamic phase behavior. In this case, the four
\]

\[
\text{individual}
\]

\[
s_{i}
\]

\[
\text{spin-spin correlations that make up the}
\]

\[
[\langle S_{k} S_{j} \rangle]
\]

\[
\text{are approximately equal:}
\]

\[
[\langle S_{k} S_{j} \rangle] = [\langle s_{i} s_{j} \rangle],
\]

\[
\text{where}
\]

\[
s_{i}
\]

\[
\text{is either}
\]

\[
of the spins contributing to}
\]

\[
S_{k}
\]

\[
\text{and}
\]

\[
s_{j}
\]

\[
\text{is either of the spins}
\]

\[
contributing to}
\]

\[
S_{j}
\]

\[
Hence, we shall use
\]

\[
[\langle S_{k} S_{j} \rangle]
\]

\[
\text{and}
\]

\[
[\langle s_{i} s_{j} \rangle]
\]

\[
\text{interchangeably in the rest of the text.}
\]

\[
\text{C. Details of numerical implementation}
\]

\[
\text{To calculate the long-range spin-spin correlation function}
\]

\[
[\langle S_{k} S_{j} \rangle],
\]

\[
\text{we start with a finite hexagonal lattice after}
\]

\[
n\text{ construction steps, with size varying between}
\]

\[
n=7–10\text{ steps}
\]

\[
(N=17\ 496–742\ 392\text{ tensors}).\ The\ bonds\ k\ and\ l\ are\ chosen}
\]

\[
to\ be\ at\ the\ maximum\ separation\ within\ the\ lattice,\ taking}
\]

\[
periodic\ boundary\ conditions\ into\ account.\ For\ a\ given\ realiza-
\]

\[
tion\ of the\ disorder,\ the\ sum\ on\ the\ right-hand\ side\ of\ Eq.}
\]

\[
(11)\ is\ evaluated\ by\ doing\ n\ TRG\ transformations,\ which}
\]

\[
yields\ the\ contraction\ in\ terms\ of\ four\ renormalized\ tensors}
\]

\[
in\ the\ n=0\ structure.\ These\ last\ four\ tensors\ are\ directly}
\]

\[
contracted.\ A\ similar\ process\ yields\ the\ value\ of\ the\ partition}
\]

\[
function\ Z\ which\ is\ the\ denominator\ in\ Eq.}
\]

\[
(11).\ The\ configurational\ average\ is\ taken\ over\ 200–300\ realiza-
\]

\[
tions,\ implemented\ by\ randomly\ assigning\ the\ J_{ij}\ on\ the\ initial}
\]

\[
\text{lattice according to the probability distribution in Eq.}
\]

\[
(5).\ The\ tensors\ on\ the\ original\ lattice,\ i.e.,\ in\ Eqs.\ (6)\ and\ (9),}
\]

\[
have\ index\ range\ d=4.\ For\ subsequent\ tensors,\ we\ use\ a\ cutoff}
\]

\[
parameter\ D=8–14.\}
\]

\[
\text{Some\ tensor\ elements\ tend\ to\ grow\ exponentially\ in\ magnitude\ as}\}
\]

\[
the\ TRG\ transformation\ is\ iterated,\ which\ poses\ potential\ numerical}
\]

\[
difficulties.\ To\ counteract\ this,\ we\ take\ advantage\ of\ the\ fact\ that\ we\ can\}
\]

\[
always\ factor\ out\ a\ constant\ from\ each\ tensor\ without\ changing\ the\ physics.\ For\ each}
\]

\[
tensor\ during\ each\ TRG\ iteration,\ the\ factor\ extracted\ is\}
\]

\[
\text{implemented by randomly assigning the}\ \text{figurational average is taken over 200–300 realizations,}
\]

\[
\text{on this extracted factor slows down the decay of most tensor}
\]

\[
elements\ to\ zero,\ which\ would\ otherwise\ lead\ to\ other\ numerical\ artifacts.\ We\ keep\ track\ of\ the\ total\ extracted\ factors}
\]

\[
051110-5
\]

\[
\text{FIG. 5. (Color online) The long-distance spin-spin correlation}
\]

\[
[\langle s_{i} s_{j} \rangle]\ as\ a\ function\ of\ temperature\ 1/J,\ calculated\ using\ the\ TRG}
\]

\[
method\ for\ bond\ dilution\ probability\ p=0.1\ and\ cutoff\ parameter}
\]

\[
D=8.\ The\ curves\ for\ four\ different\ initial\ tensor\ network\ sizes}
\]

\[
N\ are\ shown.
\]

\[
\text{FIG. 6. (Color online) The long-distance spin-spin correlation}
\]

\[
[\langle s_{i} s_{j} \rangle]\ as\ a\ function\ of\ temperature\ 1/J,\ calculated\ using\ the\ TRG}
\]

\[
method\ for\ bond\ dilution\ probability\ p=0.1\ and\ network\ size\ N}
\]

\[
=157\ 464\ text{ tensors}.\ The\ curves\ for\ four\ different\ cutoff\ parameters\ D\ are}
\]

\[
shown.
\]
in the numerator and denominator of Eq. (11), which are then used in calculating the final correlation function value.

IV. RESULTS

Representative results for the long-distance spin-spin correlation function $\langle s_i s_j \rangle$ as a function of temperature $1/J$ at bond dilution $p=0.1$ are given in Figs. 5 and 6. The former shows curves for various tensor network sizes $N$ using cutoff $D=8$, while the latter varies the cutoff $D$ at fixed size $N=157 464$. Away from the critical temperature, where widely separated spins are uncorrelated, $\langle s_i s_j \rangle=\langle s_i \rangle^2$, and we expect distinct limiting behaviors for the two different thermodynamic phases in the system: at low $1/J$ in the ferromagnetically ordered phase $\langle s_i s_j \rangle \rightarrow 1$, while at high $1/J$ in the paramagnetic phase $\langle s_i s_j \rangle \rightarrow 0$. The temperature region where one sees a smooth transition between these two regimes for finite systems, illustrated in Figs. 5 and 6, gives a rough indication of the phase-transition temperature $1/J_c$ in the thermodynamic limit. With increasing $N$ in Fig. 5 and increasing $D$ in Fig. 6, the transition becomes sharper, as our truncations converge toward the exact result for an infinite system. The probability $p=0.1$ at which these results are calculated is smaller than the threshold value $p_c=0.653$ [22], above which the triangular lattice no longer percolates. For $p > p_c$ we would not see a transition region: the paramagnetic phase exists at all temperatures since islands of ordered spins of size $\sim O(N)$ become exponentially improbable.

To obtain an accurate estimate of the exact transition temperature $1/J_c$, we can employ the following finite-size scaling relation, which describes the ratios of the correlation functions at three different system sizes $N_1$, $N_2$, and $N_3$ when $J=J_c$ [23]:

$$\ln \left( \frac{g(N_3)}{g(N_1)} \right) \frac{N_2}{N_1} = \ln \left( \frac{g(N_3)}{g(N_2)} \right) \frac{N_1}{N_2},$$

where $g(N)$ is the long-distance correlation function $\langle s_i s_j \rangle$ for network size $N$. For the $i$th system, at the temperature region where $g(N_i)$ decays rapidly to zero ($J$ just smaller than $J_i$), the decay is approximately exponential in $J$,

$$\ln [g(N_i)] = A_i J - B_i,$$

for some constants $A_i$ and $B_i$. This exponential behavior for three different system sizes is shown in Fig. 7 for $p=0.25$ and 0.55. To calculate $A_i$ and $B_i$, we do a weighted linear least-squares fit to $\ln [g(N_i)]$ vs $J$ data in a region of $J$ where the relative uncertainty (from the configurational average) for the data points is less than 15%. Plugging Eq. (13) into Eq. (12) with $J=J_c$, we can solve for $J_c$ in terms of the $A_i$, $B_i$, and $N_i$:

$$J_c = \frac{(B_2 - B_1) \ln \left( \frac{N_3}{N_2} \right) + (B_2 - B_3) \ln \left( \frac{N_2}{N_1} \right)}{(A_1 - A_2) \ln \left( \frac{N_3}{N_2} \right) + (A_3 - A_2) \ln \left( \frac{N_2}{N_1} \right)},$$

Carrying out this calculation across the entire $p$ range for $N_1=17496$, $N_2=52488$, and $N_3=157 464$ at $D=12$, we obtain the phase diagram shown in Fig. 1. For comparison we also plot the same phase diagram obtained from a rigorous approximation scheme for the bond-diluted Ising-model free energy [17], which can be considered exact on the scale of the figure. The agreement is quite close, with an average relative deviation of 1%. Two values along the curve are known exactly: $1/J_c=4/\ln 3=3.641 [24]$ at $p=0$ and the curve goes to $1/J_c=0$ at the percolation threshold $p=p_c=1/2\sin(\pi/18)=0.653 [22]$. Our results deviate from these exact values by 0.3% and 0.4%, respectively.

V. CONCLUSIONS

We have shown how the TRG approach provides an efficient and precise method for calculating thermodynamic properties of a quenched random classical model—the triangular-lattice bond-diluted Ising Hamiltonian. By expressing the partition function and related quantities such as spin-spin correlation functions in terms of tensor networks, they can be readily evaluated through TRG for large lattice sizes. In combination with finite-size scaling ideas, the result is a precise estimate of the phase diagram. If desired, convergence to the exact critical properties can be achieved by increasing the cutoff parameter defining the index range of the tensors.
The bond-diluted Ising model is only a first step in the exploration of disordered systems using TRG: the methods presented here are easily extended to frustrated Hamiltonians exhibiting spin-glass behavior and the resulting complex multicritical phase structures. The numerical accuracy of the technique will be a valuable feature in probing analytical conjectures on the exact locations of spin-glass multicritical points [25–28].

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