Order in a Spatially Anisotropic Triangular Antiferromagnet

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The phase diagram of the spin-1/2 Heisenberg antiferromagnet on an anisotropic triangular lattice of weakly coupled chains is investigated using a renormalization group analysis which includes marginal couplings important for connecting to numerical studies of this model. In particular, the relative stability of incommensurate ground states and collinear antiferromagnetic order is studied. While incommensurate spiral order is found to exist over most of the phase diagram in the presence of a Dzyaloshinskii-Moriya (DM) interaction, at small interchain coupling and extremely weak DM coupling, collinear antiferromagnetic order can survive. The implications of the renormalization group analysis for numerical studies, many of which have found spin liquid-like behaviour, are discussed.

I. INTRODUCTION

Frustrated magnets are of considerable interest because of their potential for exhibiting novel ground states in two or higher dimensions. The spin-1/2 Heisenberg antiferromagnet (HAF) on an anisotropic triangular lattice is a particularly well-studied model of frustrated magnetism and is relevant to Cs2CuCl4, a material whose neutron spectrum has been taken as evidence for close proximity to a two-dimensional spin liquid phase. Below 0.6K, Cs2CuCl4 orders into an incommensurate spiral spin density state and is well described by the spin-1/2 HAF on a triangular lattice, with interchain diagonal exchange J′ weaker than the intrachain exchange J, although weak interlayer and Dzyaloshinskii-Moriya (DM) interactions also play a role in stabilizing the ordered state.

The spiral phase with ordering wave vector qd = \pi + 2\sin^{-1}(J'/2J) is the classical ground state for the HAF on a triangular lattice for all J' < 2J. It is well-established that the nearly isotropic (J' \lesssim J) spin-1/2 HAF exhibits spiral order which smoothly connects to the three sublattice Néel order at J'=J. Several studies have proposed that, as J' is further reduced, quantum fluctuations destroy this order and stabilize a two-dimensional spin liquid phase. Although this model is in proximity to a one-dimensional spin liquid (J'=0), it lacks the features typically associated with possible spin liquid order in higher than one dimension. That is, it neither exhibits macroscopic degeneracy of the classical ground state, as occurs for Kagome or pyrochlore lattices, nor substantial ring exchange, as occurs near a metal-insulator transition. Nevertheless, essentially all calculations show that quantum fluctuations are unusually large and the local moment has been estimated to go to zero for J'/J as large as 0.9–1.2. While it has typically been assumed that the loss of spiral order signals the appearance of a quantum disordered state, Starykh and Balents using a renormalization group (RG) approach, found a collinear antiferromagnetic (CAF) state stabilized at small J'/J. They identified quantum fluctuations of order (J'/J)^2 that couple second nearest-neighbor (nn) chains antiferromagnetically, leading to CAF order, whereas a ferromagnetic second nn chain interaction would be compatible with spiral order. This result is surprising since, although quantum fluctuations will typically select a specific state from a degenerate manifold of classical ground states, it is unusual for fluctuations to stabilize an ordered state of higher classical energy. This order is rather subtle since it is only selected at O(J'/J)^4, so numerical studies taken as evidence for spin liquid behavior may also be compatible with such order, as well as with spiral order which is strongly renormalized by quantum fluctuations. Exponentially weak spiral order has been predicted within a random phase approximation which does not include the (J'/J)^4 antiferromagnetic fluctuations identified in Ref. 14. Numerical studies on multi-leg ladders find incommensurate spiral correlations with a wavelength which is strongly renormalized from the classical value and smaller than the finite system size for 0.5 < J'/J < 1.3. This provides evidence for an incommensurate spiral ground state in this range of J', but one would need to study even larger systems for smaller J' since the spiral wavelength, \lambda = 2\pi/(q - \pi), is expected to grow rapidly with decreasing J'/J.

Calculations which directly compare the energies of the CAF state and spiral state have given conflicting results. Pardini and Singh using linked cluster series expansions, found that the spiral phase, with a variational ordering wave vector, appears to have lower energy than the collinear state for J'/J \geq 0.1. They also found the ordered moment vanished rapidly with decreasing J'/J, as expected for either ordered state. By contrast, a coupled cluster method yielded a lower energy for the CAF state for J'/J \lesssim 0.6, although this method was unable to capture the vanishing moment. Neither method is strictly variational, making direct comparisons of the energies difficult to interpret, as discussed in Ref. 15. Nevertheless, both methods show that the energy difference...
between these two states at small $J'/J$ is significantly smaller than the energy scale set by quantum fluctuations, i.e., than the $O(J'^2/J)$ difference between the classical and quantum energies.

Here, we reexamine the RG approach of Ref. 14 but rather than starting by integrating out every second chain as was done in Ref. 14, we adhere more strictly to the real-space RG method and keep quantum fluctuations of $O(J'/J)^2$. These are generated by marginal (and irrelevant) couplings and are not expected to order the system as $J' \to 0$. However, these fluctuations dominate the energy and are important for interpreting numerical results as they extend over an unusually large length scale (which diverges as $J' \to 0$). Surprisingly, these are of the opposite sign to the fluctuations responsible for CAF ordering. Thus, our RG analysis elucidates the competition between spiral and CAF order. We also present numerical studies which show that ferromagnetic fluctuations dominate at all $J' < J$, but that, consistent with the RG analysis, these fluctuations only grow weakly with system size for small systems.

The remainder of this paper is organized as follows. The model and RG equations are presented in Sec. II and the general RG flows and resulting ground states for varying initial conditions are discussed in Sec. III. Sec. IV discusses the specific initial conditions appropriate for the Heisenberg model and the resulting RG analysis. The crossover from CAF to spiral order with increasing $J'$ is also discussed in Sec. IV. Numerical studies of this system are presented in Sec. V and compared to the RG results, while Sec. VI considers the effect of a weak Dzyaloshinskii-Moriya interaction. A summary and discussion of the results are given in Sec. VII. An approximate analytic solution to the RG equations, used in the analysis of the numerical studies, is given in the Appendix.

II. MODEL AND RG EQUATIONS

Here, we derive the RG equations following an approach similar to Ref. 14 but starting from short length scales and including marginal couplings and fluctuations of $O(J'/J)^2$ in order to connect to finite size studies and to study the relative stability of collinear, spiral and dimer ordered states, as summarized in Fig. 1. Our starting point is the Hamiltonian:

$$H = \sum_{n,y} \left\{ JS_{n,y} \cdot S_{n+1,y} + J'S_{n,y} \cdot (S_{n-\frac{1}{2},y+1} + S_{n+\frac{1}{2},y+1}) + D \cdot \left[ S_{n,y} \times (S_{n-\frac{1}{2},y-1} - S_{n+\frac{1}{2},y+1}) \right] \right\} \quad (1)$$

where $n$ indexes sites on the horizontal chains, $y$ is the chain label, and $J$ and $J'$ are, respectively, intra- and interchain couplings as shown in Fig. 1a. The last term in Eq. (1) is the DM interaction, where $D = D\delta_{n,1,1}$.

We first consider the case $D = 0$. The continuum approximation is made for the horizontal chains, while the other direction is kept discrete. The spin operators are written in terms of the uniform and staggered magnetizations $\mathbf{S}_{n,y} \to \mathbf{M}_{y}(x) + (-1)^y \mathbf{N}_{y}(x)$, where the subscript $y$ indexes the chains, and we use the sign convention shown in Fig. 1b.

The Hamiltonian for each chain is the Wess-Zumino-Novikov-Witten (WZNW) $SU(2)$ model which defines the fixed point of decoupled chains, perturbed by intra-chain backscattering, with coupling $\gamma_{bs}^{\frac{1}{2}}$.

$$H_{\text{intra}} = \sum_{y} \left\{ H_{y}^{\text{WZNW}} + \gamma_{bs} \int dx J_{R,y} \cdot J_{L,y} \right\} \quad (2)$$

The interchain part of $H$ in the continuum limit becomes:

$$H_{\text{inter}} = \sum_{y} \int dx \left\{ \gamma M_{y} \cdot M_{y+1} + \gamma_{\text{tw}} \frac{(-1)^y}{2} (N_{y} \cdot \partial_{x} N_{y-1} - \partial_{x} N_{y} \cdot N_{y+1}) + \cdots \right\} \quad (3)$$

where ellipses indicate irrelevant terms with more derivatives. $M_y$ is the sum of the left- and right-moving currents, $J_{L,y}$ and $J_{R,y}$, that have scaling dimension 1, so $M_y \cdot M_{y+1}$ and backscattering both have scaling dimension 2 and are marginal. The scaling dimension of $N$ is 1/2, and, therefore, that of the twist term (with coupling $\gamma_{\text{tw}}$) is 2.

In addition to the above couplings, there are two relevant and two marginal interactions that are not prohibited by any of the symmetries of this model: $\gamma_{1}N_{y} \cdot N_{y+2}$ and $\gamma_{2} \varepsilon_{y} \varepsilon_{y+2}$ with scaling dimension 1, and $\gamma_{3} (-1)^{y} (\varepsilon_{y} \partial_{x} \varepsilon_{y+1} - \partial_{x} \varepsilon_{y} \varepsilon_{y+1}) / 2$ and $\gamma_{4} M_{y} \cdot M_{y+2}$ with dimension 2. $\varepsilon$ is the staggered dimerization operator and has scaling dimension $1/2$. Third and further nn chain couplings can be ignored for small $J'/J$ because of their much smaller initial values.
The theory is regularized by imposing a short distance cut-off for how close to each other the operators that perturb $\mathcal{H}_\text{WZW}$ can be. Real space RG along $x$ is then conveniently performed using operator product expansions (OPE) of the above interaction terms at separate space-time points and integrating over short relative spatial and temporal separations. The OPEs of chiral currents can be directly derived from the OPEs of chiral fermion fields but the correct OPEs of $N$ and $\varepsilon$ require bosonization. Neglecting terms of $O(J'/J)^3$ and higher, the beta-functions for the relevant and marginal coupling constants are

$$\partial_l \gamma_{bs} = \gamma_{bs}^2 - 6g_N^2,$$

$$\partial_l \gamma_M = \gamma_M^2$$

(4)

$$\partial_l \gamma_{tw} = -\frac{1}{2} \gamma_{bs} \gamma_{tw} + \gamma_M \gamma_{tw} - 3\gamma_{tw} g_N - \frac{1}{2} \gamma_M \gamma_{\varepsilon}$$

(5)

$$\partial_l g_N = g_N - \frac{1}{2} \gamma_{bs} g_N + g_M \varepsilon_N + \frac{1}{2} \gamma_{tw} g_M + g_N g_N$$

(6)

$$\partial_l g_{\varepsilon} = g_{\varepsilon} + \frac{3}{2} \gamma_{bs} g_{\varepsilon} - \frac{3}{2} g_M g_{\varepsilon} + \frac{1}{4} \gamma_{tw} + \frac{3}{2} g_M g_{\varepsilon}$$

(7)

$$\partial_l \varepsilon_{\varepsilon} = -\frac{1}{2} \gamma_{bs} \varepsilon_{\varepsilon} - \frac{1}{2} \gamma_{tw} \varepsilon_{M} - \frac{1}{2} \gamma_{\varepsilon} g_{\varepsilon}$$

(8)

$$\partial_l g_M = \gamma_M^2 - \frac{1}{4\pi^2} \gamma_{bs} \varepsilon_M$$

(9)

$$\partial_l \varepsilon_N = -\varepsilon_N - \frac{1}{2} \gamma_{bs} \varepsilon_N - \frac{1}{4} \gamma_{tw} + g_M \varepsilon_N$$

(10)

$$\partial_l \varepsilon_M = -2 \varepsilon_M - 8\pi^2 \gamma_M^2 + g_{bs} \varepsilon_M$$

(11)

All couplings are scaled by $2\pi v = \pi^2 J$, and $\ell^l = L/L_0$, so that $l(L_0) = 0$, where $L$ is the physical length and $L_0$ is the initial length scale which has been set equal to 1 in the above equations. Eqs. (4-11) are only brought in because these couplings affect the initial values of more relevant couplings. $\varepsilon_N$ is the coupling for the interaction term $\partial N_y \cdot \partial N_{y+2}$, and $\varepsilon_M$ is that of $(M_y \cdot M_{y+2}) (J_{L,y+1} J_{R,y+1})$. Both of these are irrelevant couplings with scaling dimensions 3 and 4. The beta-functions of $\gamma_M$ and $g_M$ only describe the renormalization of the interchain backscattering part of $M_y \cdot M_{y'}$ (coupling between currents with opposite chiralities) which also are the parts that enter in the other beta-functions.

The beta-functions of Ref. [14] differ from Eqs. (4-11) in that only the first three terms in the beta-functions for $g_N$ and $g_{\varepsilon}$ (in Eqs. (5-7)) were included in Ref. [14] and the renormalization of marginal couplings other than $\gamma_{bs}$ were not considered. $\gamma_{tw}$, in particular, is needed to interpret the numerical results and to study the relative stability of the spiral and collinear AF states. As discussed below, the $\gamma_{tw}$ term in Eq. (4) is not expected to order the system, but describes the dominant fluctuations at short and intermediate distances and is important for interpreting numerical results on finite systems. The key RG equations for our study are Eqs. (4-11).

III. GENERAL RG FLOWS

At the lattice scale, only couplings present in the bare Hamiltonian, $\gamma_{tw} = \gamma_M/2 = J'/\pi^2 J$, $\gamma_{bs} = -0.23$ are nonzero. Integrating out short wavelength fluctuations up to the initial length scale $L_0$ (larger than but comparable to the lattice spacing) generates all couplings allowed by symmetry, in particular, the two relevant couplings, $g_N(0)$ and $g_{\varepsilon}(0)$. Once generated, these couplings tend to grow exponentially in $l$ (or linearly in $L$) while the marginal and irrelevant couplings grow at most logarithmically with $L$. It follows from Eqs. (6) and (7) that, in the presence of negative backscattering, $g_N$ grows faster than $g_{\varepsilon}$. Therefore, for small $J'/J$, the value of $g_N(0)$ largely determines the fate of the system, as it will reach 1 (or $J$ in unscaled units) at some length scale, $l^*$, while the other couplings will remain much smaller.

If $g_N(0)$ is positive (i.e., antiferromagnetic), it follows from Eq. (8), that $g_N(l)$ remains positive and flows to +1 at some $l^*$. In this case, second nn chains will order antiferromagnetically. This is the result found in Ref. [14], where every second chain was integrated out to give $g_N(0) = -2g_N(0)/3 = A_0^2 J'/\pi^2 J$, where $A_0^2 \approx 0.13$ is a normalization factor. The CAF state is then stabilized for small $J'/J$, by the order from disorder mechanism, when one includes the effect of $\gamma_M(l^*) \sim O(J'/J)^{5/6}$.

However, numerics on finite systems show that second nn chains are coupled ferromagnetically, not antiferromagnetically as implied by $g_N(0) > 0$. Fig. 2 shows the interchain Neel susceptibility, where a small finite staggered magnetic field is applied to one chain and the response of the second neighbor chain is calculated using exact diagonalization (ED) for 3 chains of length 12 sites or less, with open boundary conditions. For a staggered field, $h$, along $\hat{z}$, the response $\langle S_i^z \rangle/h$, where site $i$ is one of the center sites on the chain, is calculated. This response is the interchain Neel susceptibility,

$$\chi_s(L) = -i \sum_{n=1}^{L} (-1)^n \int dt \theta(t) \langle [S_i^z(t), S_{i+n}^z(0)] \rangle.$$

(12)

It is found that $\langle S_i^z \rangle$ aligns ferromagnetically with the second neighbour chain for all $0 < J' < 1$, as well as for small $J' < 0$. $\chi_s$, which is discussed further in Sec. V below, is analytic in the couplings and, for small $J'/J$, is proportional to $g_N(L)$ to leading order. Therefore, it follows from these ED results that $g_N(0) = a(J'/L) + b(J'/J)^2 + c(J'/J)^3$, where $a, b, c$ are all ferromagnetic and, in fact, ferromagnetic fluctuations dominate in these systems of up to 36 spins. $\chi_s$ calculated for 4 chains with periodic boundary conditions applied perpendicular to the chains (along $y$) yields exactly the same quadratic and cubic terms and a larger ferromagnetic quartic term. The difference in the quartic term is due to the longer range analogue of $\gamma_{tw}$ which couples third neighbour chains and which is not included in the above RG equations as it has no qualitative effect on the
FIG. 2. The response to a small staggered magnetic field, \( h \), applied to one chain is studied using exact diagonalization for 3 chains of lengths from \( L=6 \) to \( L=12 \). The response of a central spin on the second neighbor chain, \( \langle S_i^z \rangle/hL \), is shown along with polynomial fits to the data. The sign of the response is found to be such that \( \langle S_i^z \rangle \) always aligns ferromagnetically with the other chain.

The calculated \( \chi_s \) is sensitive to boundary conditions for small systems. Periodic boundary conditions (PBC) along the chains (along \( x \)) frustrate spiral correlations generated by \( \gamma_{tw} \), which we will see in the next section are connected to ferromagnetism. Indeed, for the small systems studied with PBC along \( x \) (up to 30 spins, not shown here) we found \( \chi_s \) is of order \( (J'/J)^4 \) and has the opposite sign to the data in Fig. 2. However, the fact that spins \( \vec{S}_{i,y} \) and \( \vec{S}_{i+x,y+2} \) for small \( s \) are coupled ferromagnetically at order \( (J'/J)^2 \) and higher is independent of the boundary condition and is seen even in small systems with PBC along \( x \). In particular, \( \langle \vec{S}_{i,y} \cdot \vec{S}_{i+x,y+2} \rangle \) is always positive irrespective of the boundary condition. This implies that \( g_N(0) < 0 \). In fact, for open boundary conditions, our ED studies find \( \langle (S_i^z - S_j^z) \rangle_{\text{ED}} < 0 \) for all \( x \), for all system sizes and \( J' \) values studied \( (J'/J < 0.5) \).

It follows from the RG equations that for \( g_N(0) < 0 \), \( g_N \) (\( l^* \)) can be either negative or positive, depending on the precise value of \( g_N(0) \). In this case, the flow of \( g_N \) is sensitive to the magnitude of the initial value due to the competition between \( g_N(0) < 0 \) and terms in Eq. (6) that drive \( g_N(l) \) antiferromagnetic. This sensitivity to initial conditions can be seen by numerically studying the RG flows for an initial \( g_N(0) = \alpha \gamma_{tw} \) as the constant \( \alpha \) is varied. Here, we use bare values (i.e., values at the lattice scale) for the initial values of the other couplings. RG flows are shown in Fig. 3 for \(-0.30 \leq \alpha \leq -0.26 \). For \( \alpha \geq -0.28 \), one finds that \( g_N \) flows to 1 (strong antiferromagnetic coupling) and \( \gamma_{tw} \) remains small, while for \( \alpha \leq -0.28 \), \( g_N \) flows to -1 (strong ferromagnetic coupling) and \( \gamma_{tw} \) increases marginally. As discussed below, \( g_N \rightarrow -1 \) signals spiral order, whereas \( g_N \rightarrow 1 \) signals CAF order as studied by Starykh and Balents. However, as seen in the inset of Fig. 3 for \( g_N \rightarrow 1 \), even in the case of CAF order, the initial RG flows can display increasing ferromagnetic coupling between second nn chains. In Sec. (V) it will be shown that this is the case for the Heisenberg model. In a narrow range for \( \alpha \approx -0.28 \) (which widens as \( J' \) is increased) the growth of \( g_N \) is hindered and \( \gamma_{tw} \) grows first. This crossover value, \( g_N^{\alpha_{\text{crossover}}} \), depends on \( \gamma_{ts} \) and \( g_\alpha \). Depending on initial conditions, columnar or staggered dimerization or more complicated incommensurate states can be stabilized in this crossover region, as denoted by the shaded area in Fig. 4.

In the ferromagnetic regime where \( g_N \) grows exponentially to negative values \( (g_N < g_N^{\text{crit}}(0)) \), sites along the \( y \)-direction align, consistent with zero \( y \)-component of the ordering wave vector. In this regime, \( \gamma_{tw} \), which stabilizes spiral order, grows marginally. In the classical limit, the ordering wave vector \( \mathbf{q} = (\pi + \epsilon) \mathbf{x} \) is \( (\pi + J'/J) \mathbf{x} \) for \( J' \ll J \). The effect of quantum fluctuations on \( \mathbf{q} \) or \( \epsilon \) can be determined from the RG analysis. The most robust spiral state occurs if ferromagnetism is selected at quadratic order in \( J' \). The length scale, \( l^* \), at which \( g_N \) becomes comparable to \( J \) in magnitude is inversely proportional to the initial value of \( g_N \) which, in turn, is \( \propto J^2 \) in this case. Since \( \gamma_{ts} \) changes logarithmically and remains negative as \( g_N \) grows, at this length scale we expect almost the same intrachain Hamiltonian but with a somewhat renormalized \( \gamma_{ts} \). This Hamiltonian describes interactions between blocks of Neel ordered spins.
of length $l^*$ and can be treated classically. Thus, the ground state has spiral order with $\epsilon \propto (J'/J)^3$. Since $1/\epsilon \gg l^*$ for small $J'$, the pitch of the spiral is much longer than the Neel blocks and this treatment is justified. This is a significant renormalization of the ordering wave vector toward the 1D limit of $\pi$, where the spin on neighboring antiferromagnetic chains are oriented at $\pi/2$ with respect to each other and requires that ferromagnetism is selected at quadratic order.

Even more fragile spiral order is stabilized if $\Delta g = g_N(0) - g_{\text{AF}}^\text{crit} \approx 0$ and ferromagnetism is selected at cubic or quartic order in $J'$. Then $\epsilon \propto (J'/J)^n$, where $n=4$ (or 5) for cubic (or quartic) selection. The exponentially weak spiral order, $\epsilon \sim e^{-a(J'/J)^2}$ found within a random phase approximation also follows from the RG equations if one assumes that neither $g_N$ nor $g_c$ can grow. To leading order in $J'/J$, Eq. (14) describes this exponentially weak spiral order, where $a = 2.6$ if the value $\gamma_{bs} \approx -0.38$ at $a_0$ is used. However, since there is no symmetry which prevents $g_N$ (or $g_c$) from growing at all orders, one does not expect exponentially weak spiral order to be stable for very small $J'/J$.

As $J'$ increases, even for initial conditions which favor antiferromagnetism, $\Delta g = g_N(0) - g_{\text{AF}}^\text{crit} < 0$, the RG flows move toward increasing $\gamma_{tw}$, i.e., toward the spiral state. This is because $\gamma_{tw}$ is boosted by both backscattering and $\gamma_M$. The latter enhances the spiral incommensurability, $\epsilon$, so it is larger than $e^{-a(J'/J)^2}$. For the Heisenberg model, where $\gamma_{bs}(0)$ is sufficiently negative to suppress the growth of $g_c$ relative to $g_N$, the competition is predominantly between the CAF and the spiral state. If a sufficiently strong frustrating second nn interaction along the chains is added to the Hamiltonian, the competition is then between the CAF and dimerized phase as discussed in Ref. [14].

IV. INITIAL CONDITIONS AND RG RESULTS

It follows from the above discussion of the RG flows that it is important to determine $g_N(0)$ accurately. Numerics on small systems clearly show that $g_N(0)$ is ferromagnetic, whereas Eq. (14) would naively predict that $g_N(0) \sim +\gamma_{tw}^2$. In fact, only antiferromagnetism appears to enter the RG equation for $g_N$ to all orders in $J'/J$. This would imply not only that spins on second neighbor chains are always antiferromagnetically ordered, but that the dominant fluctuations at all length scales are antiferromagnetic. Actually, one sees how second neighbor chains can be coupled ferromagnetically by considering the effect of a twist in one chain on spins in neighboring chains. Treating $\gamma_{tw} N_{y+1} \cdot \partial_x N_{y}$ as perturbations to the decoupled 1D chains, one finds in second order that fluctuations in the $y$-th chain generate a local ferromagnetic coupling, $H^{\text{eff}} \sim -\gamma_{tw}^2 (\partial_x N_y)^2 N_{y-1} \cdot N_{y+1}$. Although the static twist $\langle \partial_x N_y \rangle$ is small, the fluctuation can be $O(1)$, mediating an interaction of order $J''^2$.

The peculiar behavior where the sign of the quantum correction for $g_N$ depends strongly on scale can also be seen in the continuum theory, once the theory is regularized. The OPE between two twist terms generates a term in the effective action:

$$-\gamma_{tw}^2 \int dz dz' [\partial_x \partial_x G(z - z')] N_{y-1}(z) \cdot N_{y+1}(z').$$ (13)

Here $z = i(vt - x)$, $G(z - z') = \langle N_y(z) \cdot N_y(z') \rangle \sim 1/\sqrt{(z - z')^2 + a_c^2}$ and $a_c$ is larger than but comparable to the lattice spacing. The integrand in Eq. (13) is positive for $0 < |z - z'| < a_c$, which generates the ferromagnetic initial condition for $g_N$, but becomes negative for $|z - z'| > a_c$, favoring antiferromagnetic correlation at longer lengths.

The presence of a ferromagnetic coupling at short distances is very general and independent of the specific regularization scheme: it simply follows from the fact that $[\partial_x \partial_x G(z - z')]$ in Eq. (13) is a total derivative which integrates to zero and is negative at large distances. The presence of this total derivative implies that this term does not contribute at $q = 0$ in a gradient expansion and, consequently, is not expected to order the system. For example, if one fully integrates out every second chain to generate effective couplings between second nn chains, as was done in Ref. [14] this term vanishes. This implies that the initial value of $g_N$ at quadratic order must be such as to cancel the effect of $\gamma_{tw}^2$ in the beta-function in the $q \to 0$ limit. This places constraints on the initial conditions which are discussed below. In general, however, $g_N(0) = a J'^2 + b J'^3 + c J'^4$, where $a, b, c$ are all negative (i.e., ferromagnetic). The cubic and quartic contributions to the initial condition are related to the quadratic and cubic contributions in the beta function for $\gamma_{tw}$.

We note here that the $\gamma_{tw}$ term in the beta-function for $g_N$ is not the only term which contributes ferromagnetism at short length scales. For example, the longer range analogue of $\gamma_{tw}$ and irrelevant couplings such as $\zeta_N$ (or even higher derivative terms) contribute to the beta-function for $g_N$ in a very similar way to the $\gamma_{tw}^2$ term, but with smaller coefficients. While the inclusion of such irrelevant terms can have a quantitative effect at short lengths, the qualitative behavior of strong ferromagnetism which persists to fairly long length scales is captured by including the effects of the marginal coupling, $\gamma_{tw}$, only and is unchanged by the inclusion of more irrelevant couplings.

That $g_N$ should not grow exponentially due to the $\gamma_{tw}^2$ term is not only suggested by Eq. (13), but can be seen by expanding the interchain susceptibility, $\chi_s$, in powers of $J'$, treating the interchain interaction as a perturbation. One finds, using the simple power counting suggested by scaling, that $\chi_s(L)/L$ grows at most logarithmically in $L$ at quadratic and cubic orders, but there is a contribution at quartic order which grows linearly in $L$. It follows from this perturbative expansion that the $\gamma_{tw}^2$ term causes no exponential growth in $g_N(l)$. The initial condition which corresponds to “tuning” (no exponential
growth) is given in Eq. (8) in the Appendix, where the RG equations are solved analytically to cubic order. For \( \gamma_{bs} = 0 \) and the initial condition, \( g_N(0) = -J'^2/4 \), it follows from Eqs. (8) and (9) that \( g_N(l) \) remains constant at quadratic order. However, for nonzero \( \gamma_{bs} \), \( g_N(l) \) flows even at quadratic order and a larger ferromagnetic initial condition is needed to ensure that \( g_N \) does not grow exponentially in \( l \) at quadratic order.

While there is a ferromagnetic quartic contribution to \( g_N(0) \) from the \( \gamma^2 \) term, there is also an antiferromagnetic contribution from the \( g_M \) term in the beta-function. This term, generated within the operator product expansion technique, is analogous to the antiferromagnetic initial condition identified by Starykh and Balents. \( g_M \) is zero at the lattice scale since these couplings do not appear in the microscopic Hamiltonian, but is nonzero in subsequent RG steps and provides an initial condition equal to \( 8\gamma_{bs} J^4/\pi^6 J^4 = 0.06 J'^4/\pi^6 J^4 \) at \( \ell = 0 \) if one sets \( \gamma_M(0) = 2\gamma_{tw}(0) = 2J'/\pi^2 J \). This differs from the Starykh and Balents initial condition \( g_N(0) = A_0^2 J^4/\pi^6 J^4 \) by about a factor of 2, but both calculations rely on the continuum approximation which is only approximate near the lattice scale. Also, the two results are almost identical if one uses the value of \( \gamma_{bs} \) extrapolated to the lattice scale. An analysis of both calculations show they rely on the same physics, which involves generation of a gradient coupling between second neighbor chains (\( \zeta_N \)) and requires chiral symmetry breaking (i.e., nonzero \( \gamma_{bs} \) in the continuum RG language).

The long-distance RG results of Ref. 14 are recovered within our analysis for sufficiently small \( J' \) if the ferromagnetic initial condition associated with \( \gamma^2 \) is equal to \( g_M \) to \( O(J'/J)^4 \). In this case, the quartic term, \( g_M \), provides the essential contribution to the initial condition of \( g_N \) which drives the ordering. For this initial condition, the RG flow for small \( J' \) corresponds to one of the flows shown in Fig. 2 where \( g_N \) is initially ferromagnetic, but passes through zero at an intermediate length and then becomes large and antiferromagnetic. For small \( J' \), the intermediate length where \( g_N \) crosses over from ferromagnetic to antiferromagnetic, is proportional to \( (J'/J)^2 \), neglecting logarithmic corrections. This follows from the fact that the quadratic contribution to \( g_N(0) \) grows at most logarithmically in \( L \), while the quartic antiferromagnetic contribution grows linearly in \( L \). Consequently, the second \( n \) chains in finite systems with chains of length \( L \) will be ferromagnetically correlated for \( L < L_{FM} = A(J'/J)^2 \). The coefficient \( A \) is estimated to be 20-40 lattice spacings, depending on which value is used for the antiferromagnetic contribution to \( g_N(0) \).

A direct transition from CAF to spiral order is expected to be discontinuous, while the RG flows change continuously. Nevertheless, one can extract some information about this transition from the RG analysis. As \( J' \) increases, the RG flows move toward larger \( \gamma_{tw} \) at \( l^* \) which shows a tendency of moving toward spiral order. From the numerical solution of the beta-functions of Eqs. (11)-(13), it follows that \( J'_c \sim 0.3 \), where \( J'_c \) is defined as the value at which \( \gamma_{tw}(l^*) \) first reaches \( J \) while \( |g_N(l^*)| \leq J \). For \( \gamma_{bs}(0) = -0.23 \), \( g_N(l^*) \) remains small compared to \( J \) at this \( J' \), so the RG predicts that there is no intermediate dimer phase between the CAF and spiral ordered phases. This estimate for \( J_c \) results from using the value \( A_0^2 J^4/\pi^6 J^4 \) for the AF contribution to the initial condition and setting the ferromagnetic initial condition or tuning as discussed at the end of the Appendix.

Terms higher order than \( (J'/J)^4 \) and irrelevant couplings which are ignored, as well as exactly where one terminates the RG flows, can all affect \( J'_c \), so \( J'_c \sim 0.3 \) is only a crude estimate. The main reason for the somewhat small value of \( J'_c \) is that CAF is only selected at quartic order, while the competing marginal coupling, \( \gamma_{tw} \), is linear in \( J' \) and boosted both by backscattering and by \( \gamma_M \), which is also linear in \( J' \). We note that the estimate of \( J'_c \) is compatible with the observation of spiral correlations at \( J' = 0.5 \) in numerical studies of multi-leg ladder systems.

V. NUMERICAL RESULTS

The ED results shown in Fig. 2 show only ferromagnetism at all \( J' \), but the system sizes are not large enough to determine whether the strength of the ferromagnetism is changing with increasing system size for small \( J' \). To address this, we turn to a more detailed analysis of the numerical studies of the interchain susceptibility, \( \chi_s \), using density matrix renormalization (DMRG) to study larger systems. Specifically, we address the question of what initial conditions are compatible with the study of finite systems or, alternatively, are finite size studies compatible with the RG analysis. Using finite size scaling, the susceptibility \( \chi_s(L_i, \{g_i(0)\}, L_0) \) of the system with size \( L = L_0 e^l \) with couplings \( \{g_i(0)\} \) defined at scale \( L_0 \) (\( l = 0 \)) can be related to the susceptibility of the system with size \( L_0 \) as

\[
\chi_s(L, \{g_i(0)\}, L_0) = \frac{L}{L_0} [1 - \gamma_{bs}(L_0 l)]^{1/2} \chi_s(L_0, \{g_i(l)\}, L_0),
\]

where the linear \( L \) dependence in the prefactor is due to \( \chi_s \) having scaling dimension 1 in the absence of the backscattering, and the second factor is the contribution of the running backscattering which modifies the scaling dimension of \( \chi_s \). For small \( g_N(0) \) (small \( J' \)), \( \chi_s(L_0, \{g_i(l)\}, L_0) \) is analytic in the couplings and proportional to \( g_N(l) \) to leading order, and we have \( \chi_s(L) \propto (L/L_0) [1 - \gamma_{bs}(L_0 l)]^{1/2} \chi_s(L_0, \{g_i(l)\}, L_0) \). There is no further quantum correction to this relation to leading order in \( J'/J \), since \( g_N(l) \) is fully renormalized and includes all quantum fluctuations.

Since 3 chains captures all contributions to \( g_N \) and \( \chi_s \) to order \( (J'/J)^3 \), as well as the key \( (J'/J)^4 \) fluctuations that drive CAF order, we confine our studies to 3-chain systems. The interchain susceptibility is studied using ED and DMRG for the HAF on 3 chains with open
boundary conditions for $24$ to $84$ spins ($L=8$ to $28$); ED was used for up to $36$ spins. Up to $m = 2600$ states were kept in the DMRG, while typically keeping the precision $\epsilon \leq 10^{-8}$. The results are shown in Fig. 4. For all values of $0 < J' < J$, $\chi_s$ was found to be ferromagnetic. As noted earlier, ED studies also found that the correlation between second nn chains has quadratic, cubic, quartic (and higher order) in $J'$ contributions which are all ferromagnetic for $L \leq 12$ (as expected from analyzing the $\gamma_{tw}$ term), and the additional quartic contribution from $4$ chains is also ferromagnetic. There is no sign in the data of a turnover to negative values of $\chi_s$ expected for AF correlations. As $J'/J$ increases, the length scale at which antiferromagnetism should be observable if the CAF state is stable becomes shorter. For example, at $J'/J = 0.5$, the RG analysis predicts that one should see a turnover in $\chi_s$ for $L \geq 20$, although we don’t expect RG to be quantitatively accurate at such large $J'/J$. As $J'/J$ increases, higher order fluctuations that are not included in the RG and that are not fully captured by studying $3$ chains, can either further stabilize or destabilize CAF order.

While the extracted value of $\gamma_{bs}(L_0)$ is substantially closer to zero than the value of $-0.19$ for periodic boundary conditions, this is consistent with an independent calculation of $\chi_s$ for a single chain. For short chains, open boundary conditions are known to favor dimerization relative to periodic boundary conditions. The fact that the ratio of $\gamma_{tw}(0)/\gamma_M(0)$ extracted from the numerical data is noticeably larger than the ratio at the lattice scale can be attributed to the effect of irrelevant couplings which contribute ferromagnetism in an analogous way to the $\gamma_{tw}^2$ term.

Although the extracted initial conditions are such that $g_N$ flows to a large ferromagnetic value, which would seem to indicate spiral order, the deviation from tuning at both quadratic and cubic orders is sufficiently small to be compatible with finite size effects. For the values of $\gamma_{tw}(0)$, $\gamma_{tw}(0)$, and $\gamma_M(0)$ extracted from the data, tuning corresponds to $g_N(0) = -0.0447J'^2 - 0.0479J'^3 + O(J'/J)^4$. Therefore the quadratic (cubic) term deviates by $1\%$ ($12\%$) from the value predicted from the RG equations for order selected at $O(J'/J)^2$. Given the uncertainty introduced by finite size effects for $10 < L < 30$ and the approximations made in the RG, the numerics for small $J'$ are consistent with no order being selected to cubic order, while the lack of any tendency toward antiferromagnetism with increasing $L$ for $J'/J \geq 0.5$ suggests the CAF is not stable for these larger values of $J'$. The numerics also confirm the RG prediction that, not only is there ferromagnetism at the lattice scale for all values of $J'/J$, but this ferromagnetism continues to grow to fairly long length scales. Ideally, one would like to study the quartic term for small $J'$ as a function of system size since the RG analysis predicts that CAF order is selected by an initial condition for $g_N$ which deviates from tuning by about $20\%$ at quartic order. However, this would require studying larger system sizes while keeping more states in the DMRG calculations and is beyond the scope of this study.

VI. DZYALOSHINSKII-MORIYA INTERACTION

It is also interesting to consider the effect of a non-zero DM interaction in this RG picture since it is known that the DM interaction further stabilizes spiral order in this model. In the continuum limit, the DM interaction can be written as $\epsilon^{ab}_{N_y} N_y^{a} N_{y+1}^{b}$ with the initial condition $g_D(0) = 2|D| = 2D/\pi^2J$. Note that this term breaks the $SU(2)$ symmetry of the original model and will order the spins in a plane perpendicular to the direction of $D$. Just like the $g_N N_y \cdot N_{y+2}$ term, the DM interaction has scaling dimension $1$ and is relevant. It flows according to the following beta-function:

$$\partial_t g_D = g_D - \frac{1}{2} \gamma_{bs} g_D - 4 g_N g_D + \frac{1}{2} \gamma_M g_D.$$  

FIG. 4. The staggered Neel susceptibility, $\chi_s$, for $3$ chains as a function of chain length, $L$, at different $J'$ values, calculated by ED and DMRG. The sign of $\chi_s$ is such that second nn chains are ferromagnetically coupled for all $L$ and $J'$ studied.
The DM interaction also introduces a $-2g_N^2$ term (for components perpendicular to $\mathbf{D}$) in the beta-function of $g_N$, Eq. [4]. In addition to getting some boost from the marginal backscattering and $\gamma_M$, the DM interaction both is enhanced by and promotes ferromagnetic $g_N$. Consequently, it suppresses CAF order relative to spiral order. In any region of the phase diagram where spiral order is stable for $D = 0$, the DM interaction will further stabilize this phase relative to CAF order.

Since both $g_D$ and $g_N$ have the same exponential growth for small $J'$, a DM interaction with $g_D(0)$ greater than the untuned (antiferromagnetic) part of $g_N(0)$ will overcome the CAF order as $g_D$ will grow to be of $\mathcal{O}(1)$ first. The DM interaction favors neighboring Neel chains to be aligned perpendicular to each other, but in the presence of $\gamma_{tw}$ (which grows marginally) a spiral state will be stabilized. This suggests the phase diagram shown in Fig. 6 with a transition between the CAF and spiral states at $D \sim J'/J^3$ for small $J'/J$. This transition is expected to be first order, so the RG crossover between these two states is only approximate. However, because CAF order is only weakly favored, at order $(J'/J)^4$, the maximum $D$ for which CAF order survives will also be very small and is estimated from the RG analysis to be less than $10^{-4}J$ if $J' \lesssim 0.3J$. Even if the interchain coupling for Cs$_2$CuCl$_4$ is such as to stabilize CAF order in the absence of any DM interaction, the estimated DM interaction for Cs$_2$CuCl$_4$, $D \approx 0.05J$, is much greater than what is required to stabilize spiral order.

In summary, the full RG equations for the HAF on an anisotropic triangular lattice, including the marginal coupling $\gamma_{tw}$ which favors spiral order, describe the competition between CAF and spiral order. A tiny perturbation of $\mathcal{O}(J'/J)^4$ can tilt the balance between these two states at small $J'/J$, while a larger perturbation is needed to stabilize dimer order. As predicted by Starykh and Balents, the CAF is stable at sufficiently small $J'/J$, but either a DM interaction or a ferromagnetic second neighbour interchain interaction of $\mathcal{O}(J'/J)^4$ would stabilize an incommensurate spiral state. By contrast, an $\mathcal{O}(J)$ intrachain interaction that pushes $\gamma_{tw}$ toward zero or an interchain dimer coupling which is larger than $\mathcal{O}(J'/J)^4$ is needed to stabilize dimer order.

The RG analysis suggests a transition from CAF to spiral order as $J'$ increases, without an intermediate dimer phase. This transition is estimated to occur at $J'_c \lesssim 0.3J$, although this estimate is based on a number of approximations. That the estimate is noticeably reduced from $J'_c \sim J$ results from the fact that the order is only selected at quartic order in $J'$, while the coupling that drives spiral order, $\gamma_{tw}$, is $\sim J'$ at short distances and is boosted by backscattering and by $\gamma_M$. This estimate of $J'_c$ is compatible with DMRG studies which find evidence in favor of spiral order for $J' \geq 0.5J$. Other studies have concluded that spiral order is lost at significantly larger values of $J'/J$, such as at $J'/J \sim 0.9$. However, numerics which are interpreted as loss of spiral order could be compatible with the weak spiral order expected in the presence of quantum fluctuations. Futhermore, since the wavelength of the spiral grows rapidly with decreasing $J'/J$ and its energy lies so close to that of the CAF, as well as to many disordered states, it is important to use open boundary conditions in finite size studies.

In addition to elucidating the competition between CAF and spiral order, it is necessary to include the marginal coupling $\gamma_{tw}$ and its effect on $g_N$ in the RG analysis in order to connect to numerical studies on finite systems and to understand the behavior of the infinite system at all but the longest length scales for small values of $J'/J$. $\gamma_{tw}$ gives rise to fluctuations which cou-
ple second nn chains ferromagnetically at short lengths and which persist over long length scales. Since these fluctuations are at a different q-vector than the CAF order, they are quite distinct from the fluctuations associated with the Goldstone mode. It follows from the RG, that for systems of size $L$ along the chain direction with $L < L_{FM} = A(J/J')^2$, the second neighbour chains are ferromagnetically coupled even for values of $J'/J$ where CAF order is predicted.

For the infinite system, even in the CAF state, the static interchain spin-spin correlation function, $C_2(x) = \langle (-1)^x \vec{S}_{i,y} \cdot \vec{S}_{i+x,y+2} \rangle$, is ferromagnetic and of order $(J'/J)^2$ at $x = 0$. The RG analysis suggests that these ferromagnetic correlations persist to quite large $x$ since $g_N(L)$ is ferromagnetic and increasing in magnitude until a length scale which is smaller than, but the same order as, $L_{FM} \sim (J/J')^2$. The numerics is also consistent with this and, together with the RG analysis, suggests that the antiferromagnetism is hidden by larger ferromagnetic fluctuations except at very long length scales. One might be able to see these ferromagnetic correlations in the CAF state using cluster or series expansion calculations for the infinite system.

Ignoring the effect of backscattering, since the scaling dimension of the Neel vector is 1/2, it follows that the CAF moment scales as $(J'/J)^2$, in contrast to the case of unfrustrated coupled chains where the ordered moment scales as $\sqrt{J'/J}$ without backscattering. Given the small moment and long length scales, it is extremely challenging to determine the nature of the ground state for small $J'/J$ from finite system size studies. The interchain Neel susceptibility, $\chi_s$, together with finite size scaling may provide one fruitful avenue for such studies. For example, one could simply look for any indication of a sign change in $\chi_s$ with increasing $L$ for $J'/J < 0.5$. Our own numerical studies were restricted to $L < 30$, because of the high precision required to extract RG parameters. We found no evidence of a sign change, but, to within the expected accuracy, the numerics are consistent with the RG prediction that quadratic and cubic (in $J'/J$) fluctuation effects do not select any order.

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**Appendix: Approximate Analytic Solutions**

To better understand the flow of $g_N$ and $\gamma_{tw}$ under the RG, one may attempt solving a reduced subset of the given beta-functions (Eqs. [4-8]) analytically. If one drops terms in the beta-functions that contribute at quartic and higher orders (in $J'/J$ to $g_N$, partial analytic solutions can be obtained which yield insight into the initial conditions corresponding to “tuning”, i.e., to no exponential growth in $g_N$. This leaves us with the following reduced beta-functions:

$$\partial_t \gamma_{bs} = \frac{\gamma_{bs}^2}{1 - \gamma_{bs}(0)} , \quad \partial_t \gamma_M = \frac{\gamma_M(0)}{1 - \gamma_M(0)}$$ (A.1)

$$\partial_t \gamma_{tw} = -\frac{1}{2} \gamma_{bs} \gamma_{tw} + \gamma_M \gamma_{tw}$$ (A.2)

$$\partial_t g_N = g_N - \frac{3}{2} \gamma_{bs} g_N + \frac{3}{2} \gamma_{tw}^2$$ (A.3)

which lead to the analytic expressions:

$$\gamma_{bs}(l) = \frac{\gamma_{bs}(0)}{1 - \gamma_{bs}(0)l} , \quad \gamma_M(l) = \frac{\gamma_M(0)}{1 - \gamma_M(0)l}$$ (A.4)

$$\gamma_{tw}(l) = \frac{\gamma_{tw}(0)}{1 - \gamma_{tw}(0)l}$$ (A.5)

$$g_N(l) = \left[ \frac{\gamma_{tw}(0)}{4} \int_0^l e^{-t} \sqrt{1 - \gamma_{bs}(0)t} dt + g_N(0) \right] e^{l} \sqrt{1 - \gamma_{bs}(0)l}$$ (A.6)

For a non-zero $\gamma_M(0)$, the integral in Eq. A.6 cannot be expressed in terms of elementary functions. However, assuming $\gamma_M(0) l \ll 1$, it is possible to expand $\frac{1}{(1 - \gamma_M(0)l)^{1/2}}$ and find an expression for $g_N(l)$ as series of lower incomplete gamma-functions:

$$g_N(l) = \left[ \frac{\gamma_{tw}(0)}{4} e^{-\gamma_{tw}(0)} \sqrt{-\gamma_{bs}(0)} \sum_n (n+1) \gamma_M^n F_n(l) + g_N(0) \right] e^{l} \sqrt{1 - \gamma_{bs}(0)l}$$ (A.7)

were $F_n(l)$ is given recursively by:

$$F_n(l) = \left[ \Gamma_L(n + \frac{3}{2}) - \Gamma_L(n + \frac{3}{2} - \frac{1}{\gamma_{bs}(0)}) - \sum_{m=1}^n \gamma_{bs}^m (n - m)! F_{n-m}(l) \right]$$ (A.8)

Each term in Eq. (A.7) is accompanied by a power of $\gamma_M(0)$, and also we have a $\gamma_{tw}(0)$ factor that multiplies the sum. Since the above analytic expressions for the couplings were derived by neglecting quartic and higher order contributions, we dismiss all terms in the expansion except the first two terms. Finally, using the above
analytic expressions, the tuned initial condition for the Neel-Neel coupling, \( g_N^{(a)}(0) \), is found (\( \gamma_{bs}(0) = -0.23 \)):

\[ g_N^{(a)}(0) = -\left[0.27620(J'/J)^2 + 1.20152(J'/J)^3 + \mathcal{O}(J'/J)^4\right]. \]  

(A.9)

It is also possible to determine the coefficient of the quartic term in the above expansion numerically which gives 8.0. Note that we have taken \( g_N^{(a)}(0) \) as the initial value for which \( g_N(\ell_{\text{final}}) = 0 \) (\( \gamma_{tw}(\ell_{\text{final}}) = 1 \)) for which any \( J' \lesssim 0.2 \) is not any different from other ways of defining tuning (e.g. \( g_N(\ell_{\text{final}}) = -1 \)). However, the estimated value, \( J'/J \), for the transition from CAF to spiral, would be smaller if \( g_N(\ell_{\text{final}}) < 0 \) was used.

Finally, note that in the above calculation \( \gamma_{bs}(0) = -0.23 \) was used which is the coupling of backscattering term at \( a_0 \) rather than \( a_0 \) where \( \gamma_M \) and \( \gamma_{tw} \) have their bare values. Of course nothing is special about \( a_0 \) and one can repeat the same analysis at any arbitrary length, knowing the values of the couplings at that length scale. Thus what has been neglected is the small growth in \( \gamma_M \) and \( \gamma_{tw} \) from \( a_0 \) to \( 4a_0 \). Taking into account this growth of these couplings, the the quadratic and cubic parts of \( g_N^{(a)}(0) \) become, respectively, 0.291374 and 1.31288.

1 See, for example, L. Balents, Nature 464, 199 (2010) and references therein.
18 A. Weichselbaum and S. White, (to be published).
27 The only omitted marginal \( \mathcal{O}(J'/J)^4 \) term in the presented set of beta-functions is a long-range analogue of \( \gamma_{tw} \) that couples \( N \) and \( \partial_x N \) on chains three chains apart. The inclusion of this term in the beta-functions only introduces a small quantitative change and has no qualitative effect on the behaviour of the running couplings.
28 S. Eggert, Phys. Rev. B 54, R9612 (1996). Note that \( \gamma_{bs} = -0.23 \) is an estimated value at \( 4a_0 \).
29 We thank Leon Balents and Oleg Starykh for pointing this out.