Two-band electronic metal and neighboring spin Bose-metal on a zigzag strip with longer-ranged repulsion

Hsin-Hua Lai and Oleksii I. Motrunich
Department of Physics, California Institute of Technology, Pasadena, California 91125, USA
(Received 11 November 2009; published 5 January 2010)

We consider an electronic model for realizing the spin Bose-metal (SBM) phase on a two-leg triangular strip—a spin liquid phase found by Sheng et al. [Phys. Rev. B 79, 205112 (2009)] in a spin-1/2 model with ring exchanges. The SBM can be viewed as a “C1S2” Mott insulator of electrons where the overall charge transporting mode is gapped out. We start from a two-band “C2S2” metal and consider extended repulsion motivated by recent ab initio derivation of electronic model for k-ET spin liquid material [K. Nakamura et al., J. Phys. Soc. Jpn. 78, 083710 (2009)]. Using weak coupling renormalization group analysis, we find that the extended interactions allow much wider C2S2 metallic phase than in the Hubbard model with on-site repulsion only. An eight-fermion umklapp term plays a crucial role in producing a Mott insulator but cannot be treated in weak coupling. We use bosonization to extend the analysis to intermediate coupling and study phases obtained out of the C2S2 metal upon increasing overall repulsion strength, finding that the SBM phase is a natural outcome for extended interactions.

DOI: 10.1103/PhysRevB.81.045105

PACS number(s): 71.10.Hf, 71.10.Pm

I. INTRODUCTION

There has been much recent interest in gapless spin liquids stimulated by the appearance of several experimental candidates, including two-dimensional (2D) triangular lattice based organic compounds

$$\kappa$$-(ET)$_2$Cu$_2$(CN)$_3$ and $\text{EtMe}_3\text{Sb}[\text{Pd(dmit)}]_2$ and three-dimensional (3D) hyperkagome material Na$_2$Ir$_3$O$_6$. One line of theoretical ideas considers states with a Fermi surface of fermionic spinons.7–10 For the 2D spin liquids, such a state arises as a good variational wave function\textsuperscript{7} for an appropriate spin model with ring exchanges; it is also an appealing candidate for the Hubbard model near the Mott transition.$^{8,11,12}$ Theoretical description of such states leads to a U(1) gauge theory (see Ref. 13 for a review).

Variational studies are not sufficient to prove that a given state is realized and the gauge theory is not fully reliable in 2D. Driven by the need for a controlled theoretical access to such phases, Ref. 14 considered the Heisenberg plus ring exchanges model on a two-leg triangular strip (so-called zigzag chain).\textsuperscript{15,16} Using numerical density matrix renormalization group (DMRG), variational Monte Carlo (VMC), and analytical bosonization treatment, Ref. 14 found a ladder descendant of the 2D spin liquid in a broad range of parameters and dubbed this phase “spin Bose metal” (SBM). The name refers to metal-like itinerancy present in the spin degrees of freedom, while there is no electric transport to speak of in the spin-only model, which is bosonic model microscopically.

A low-energy field theory\textsuperscript{14} for the zigzag SBM phase can be obtained by employing bosonization to analyze the spinon-gauge theory (the slave particle approach also underlies the VMC trial states). An alternative derivation of the SBM theory is to consider an interacting model of electrons hopping on the zigzag chain and to drive a transition from a two-band metal to a particular Mott insulator. Specifically, let us start in the metallic phase with two gapless charge modes and two gapless spin modes—so-called “C2S2” metal. We can imagine gapping out just the overall charge mode to obtain a “C1S2” Mott insulator with one gapless “charge” mode and two gapless spin modes, where the former represents local current loop fluctuations and does not transport charge along the chain. This is precisely the SBM phase. If one thinks of a spin-only description of this Mott insulator, the gapless charge mode can be interpreted as spin singlet chirality mode. Ref. 14 also identified a valid umklapp term that can drive the electron system to the C1S2 phase.

In this paper, we focus on realizing such scenario for the SBM in explicit and realistic electronic models. Hubbard model on the zigzag chain ($t_1-t_2-U$ chain) has received much attention.\textsuperscript{17–22} For free electrons, the two-band metal appears for $t_2/t_1 > 0.5$. However, in the case of Hubbard interaction, weak coupling approach\textsuperscript{18,19} finds that this phase is stable only over a narrow range $t_2/t_1 \in [0.5, 0.57]$, while a spin gap opens up for larger $t_2/t_1$. The umklapp that can drive a transition to a Mott insulator requires eight fermions and is strongly irrelevant at weak coupling. Prior work\textsuperscript{17,18,23} focused on the spin-gapped metal and eventual spin-gapped insulator for strong interaction, while the C1S2 spin liquid phase was not anticipated.

There have also been numerical DMRG studies of the Hubbard model.\textsuperscript{19–22} The focus has been on the prominent spin-gapped phases and, in particular, on the insulator that is continuously connected to the dimerized phase in the $J_1-J_2$ Heisenberg model, which is appropriate in the strong interaction limit $U \gg J_1, J_2$. The C2S2 metallic phase and possibility of nearby spin liquid on the Mott insulator side in the Hubbard model have not been explored. We hope our work will motivate more studies of this interesting possibility in the Hubbard model with intermediate $U$ close to the C2S2 metal.

Since the C2S2 metallic phase is quite narrow in the Hubbard model, we would like to first widen the C2S2 region. To this end, we explore an electronic model with extended repulsive interactions.\textsuperscript{24} Such interactions tend to suppress instabilities in the electronic system, similar to how long-ranged Coulomb repulsion suppresses pairing in metals.
They are also more realistic than the on-site Hubbard, particularly for materials undergoing a metal-insulator transition where there is no conduction band screening on the insulator side. Thus, recent ab initio model construction for the κ-(ET)$_2$Cu$_2$(CN)$_3$ material found significant extended interactions in the corresponding electronic model on the half-filled triangular lattice.\textsuperscript{25,26}

Applying weak coupling renormalization group (RG) approach to the zigzag ladder system,\textsuperscript{17,18,23,27} we indeed find that extended interactions open a much wider window of the C2S2 metal phase. Building on this, we then use bosonization approach to explore a transition to a Mott insulator upon increasing the overall repulsion strength. We find that such longer-ranged interactions can drive the system into the C1S2 spin liquid Mott insulator rather than a spin-gapped insulator. This bodes well for finding spin liquid phases in more realistic electronic models for materials near the metal-insulator transition.

The paper is organized as follows. In Sec. II, we set up the weak coupling RG (Refs. 18, 23, and 27) and open a much wider window of the metallic C2S2 phase by introducing realistically motivated longer-ranged repulsion. In Sec. III, we use bosonization to extend the analysis to intermediate coupling. We gradually increase the overall repulsion strength and determine thresholds for a Mott transition driven by the eight-fermion umklapp term and also for spin gap instabilities, thus mapping out phases neighboring the C2S2 metal. In Sec. IV, we summarize our results and conclude with some discussion.

II. WEAK COUPLING ANALYSIS OF $t_1$-$t_2$ MODEL WITH EXTENDED REPULSION: STABILIZING C2S2 METAL

A. Setup for two-band electron system

We consider half-filled electronic $t_1$-$t_2$ model with extended interaction described by the Hamiltonian $H=H_0+H_V$, with

$$H_0 = -\sum_{x,a} \left[ t_1 c_{a\uparrow}^\dagger(x)c_{a\uparrow}(x+1) + t_2 c_{a\downarrow}(x)c_{a\downarrow}(x+2) + \text{H.c.} \right],$$

$$H_V = \frac{1}{2} \sum_{x,x'} V(x-x')n(x)n(x').$$

Here $c^\dagger$ is fermion annihilation (creation) operator, $x$ is a site label on the one-dimensional (1D) chain, and $a=\uparrow,\downarrow$ is a spin index; $n(x) = \sum_{\alpha} c_{\alpha\downarrow}^\dagger(x)c_{\alpha\downarrow}(x)$ is electron number on the site.

In weak coupling, the kinetic energy Eq. (1) gives free particle dispersion

$$\epsilon(k) = -2t_1 \cos(k) - 2t_2 \cos(2k).$$

For $t_2/t_1 > 0.5$, there are two sets of Fermi points at wavevectors $\pm k_{F1}$ and $\pm k_{F2}$ as shown in Fig. 1. We adopt the same conventions as in Ref. 14. Fermions near $k_{F1}$ and $k_{F2}$ are moving to the right, and the corresponding group velocities are $v_1,v_2 > 0$. Electrons are at half-filling, which implies $k_{F1}+k_{F2}=-\pi/2 \bmod 2\pi$ for the choices as in Fig. 1.

The electron operators are expanded in terms of continuum fields,

$$c_{a\alpha}(x) = \sum_{P,a} \epsilon_P^{\alpha\alpha'} c_{Paa},$$

with $P=R/L=+/-$ denoting the right and left movers and $a=1,2$ denoting the two Fermi seas.

Four-fermion interactions can be conveniently expressed in terms of chiral currents,\textsuperscript{14,23,27}

$$J_{Pab} = \sum_{\alpha} \epsilon_P^{\alpha\alpha'} c_{Paa},$$

$$\tilde{J}_{Pab} = \sum_{\alpha,\beta} \phi_{ab}^{\alpha\beta} c_{Pab}. \tag{6}$$

Most general four-fermion interactions can be written as

$$\mathcal{H}_{RL}^\rho = \sum_{a,b} \left( w_{ab}^\rho J_{Rab} J_{Lab} + \phi_{ab}^\rho J_{Rab} J_{Lbb} \right), \tag{7}$$

$$\mathcal{H}_{RL}^\sigma = -\sum_{a,b} \left( w_{ab}^\sigma \tilde{J}_{Rab} \cdot \tilde{J}_{Lab} + \phi_{ab}^\sigma \tilde{J}_{Rab} \cdot \tilde{J}_{Lbb} \right), \tag{8}$$

$$\mathcal{H}_{\text{chiral}}^\rho = \frac{1}{2} \sum_{a} C_{aa}^\rho \left( J_{Raa} J_{Raa} + J_{Laa} J_{Laa} \right) + C_{12}^\rho \left( J_{R11} J_{R22} + J_{L11} J_{L22} \right), \tag{9}$$

$$\mathcal{H}_{\text{chiral}}^\sigma = -\frac{1}{2} \sum_{a} C_{aa}^\sigma \left( \tilde{J}_{Raa} \cdot \tilde{J}_{Raa} + \tilde{J}_{Laa} \cdot \tilde{J}_{Laa} \right) - C_{12}^\sigma \left( \tilde{J}_{R11} \cdot \tilde{J}_{R22} + \tilde{J}_{L11} \cdot \tilde{J}_{L22} \right). \tag{10}$$

Here $\mathcal{H}_{RL}^\rho$ are terms that connect right and left movers, while $\mathcal{H}_{\text{chiral}}^\rho$ are chiral terms with all fermions moving in the same direction.

Consider the couplings in $\mathcal{H}_{RL}$. We have $w_{11}=w_{22}=0$ (convention), $w_{13}=w_{21}$ (from Hermiticity), and $\lambda_{12} = \lambda_{21}$ (from $R \rightarrow L$ symmetry). Thus there are 8 independent couplings: $w_{12}^\rho, \lambda_{11}^\rho, \lambda_{22}^\rho, \text{and } \lambda_{12}^\rho$. Note that there are no four-
fermion umklapp terms in our two-band system.

In the specific lattice model, we expand the interactions [Eq. (2)] in terms of the continuum fields and find “bare” values of the couplings,

\[ \lambda_{11}^\rho = V_{Q=0} - \frac{V_{2k_F}}{2}, \]
\[ \lambda_{22}^\rho = V_{Q=0} - \frac{V_{2k_F}}{2}, \]
\[ \lambda_{12}^\sigma = 2V_{2k_F}, \]
\[ \lambda_{22}^\sigma = 2V_{2k_F}, \]
\[ w_{12}^\rho = V_{k_F-k_F} - \frac{V_{\pi/2}}{2}, \]
\[ w_{12}^\sigma = 2V_{\pi/2}, \]
\[ C_{11}^\rho = C_{22}^\rho = V_{Q=0} - \frac{U}{2}, \]
\[ C_{12}^\rho = V_{k_F-k_F} - \frac{V_{\pi/2}}{2}, \]
\[ C_{11}^\sigma = C_{22}^\sigma = 2U, \]
\[ C_{12}^\sigma = 2V_{k_F-k_F}. \]

Here \( V_Q = \sum_{\epsilon=\pm} V(x-x') e^{iQ(x'-x)} = V_{\epsilon=0} \) since \( V(x-x') = V(x-x') \). We have also used explicitly \( k_F + k_F = -\pi/2 \).

The terms \( H_{\text{chiral}} \) renormalize “velocities” of various modes. In the weak coupling RG analysis, they only generate higher-order contributions and are therefore not important. The RG equations below contain only couplings from \( H_{\text{RL}} \). On the other hand, the chiral interactions are important in the intermediate coupling analysis to be done in Sec. III, which is why we have listed their values as well. The on-site coupling \( U = V(x-x') = 0 \) appears explicitly in \( C_{11}^\sigma \) and \( C_{22}^\sigma \) because of our more careful treatment of the on-site interaction, which we first write as \( U_{1}(x) n_{1}(x) \) and then insert the continuum fields (and bosonize in Sec. III).

B. Weak coupling renormalization group

The RG equations in the two-band system are \cite{18,23,27}

\[ \lambda_{11}^\rho = -\frac{1}{2\pi v_1} \left[ (w_{12}^\rho)^2 + \frac{3}{16} (w_{12}^\sigma)^2 \right], \]
\[ \lambda_{22}^\rho = -\frac{1}{2\pi v_2} \left[ (w_{12}^\rho)^2 + \frac{3}{16} (w_{12}^\sigma)^2 \right], \]
\[ \lambda_{11}^\sigma = -\frac{1}{2\pi v_1} \left[ (w_{12}^\sigma)^2 + \frac{3}{16} (w_{12}^\sigma)^2 \right], \]
\[ \lambda_{22}^\sigma = -\frac{1}{2\pi v_2} \left[ (w_{12}^\sigma)^2 + \frac{3}{16} (w_{12}^\sigma)^2 \right], \]
\[ \lambda_{12}^\rho = -\frac{1}{\pi (v_1 + v_2)} \left[ (w_{12}^\rho)^2 + 4w_{12}^\rho w_{12}^\sigma \right], \]
\[ \lambda_{12}^\sigma = -\frac{1}{\pi (v_1 + v_2)} \left[ (w_{12}^\sigma)^2 + 4w_{12}^\rho w_{12}^\sigma \right], \]
\[ w_{12}^\rho = -\Lambda w_{12}^\rho - \frac{3}{16} \Lambda w_{12}^\sigma, \]
\[ w_{12}^\sigma = -\Lambda w_{12}^\sigma - \left( \frac{\Lambda^\rho}{2} + \frac{\Lambda^\sigma}{2} \right) w_{12}^\rho. \]

Here \( \dot{O} = \partial O / \partial \ell \), where \( \ell \) is logarithm of the length scale. We have also defined

\[ \Lambda^\rho = \frac{\lambda_{11}^\rho}{2\pi v_1} + \frac{\lambda_{22}^\rho}{2\pi v_2} - \frac{2\lambda_{12}^\rho}{\pi (v_1 + v_2)}. \]

Details of our system enter through the band velocities \( v_1, v_2 \), and the initial conditions [Eqs. (11)–(18)].

C. Fixed point for stable C2S2 phase

We are primarily interested in the stability of the two-band metallic phase with two gapless charge and two gapless spin modes—C2S2 in the notation of Ref. 23. In the RG, this phase is characterized as having no divergent couplings. Before proceeding with detailed numerical studies of the flow Eqs. (23)–(30), we can describe such stable C2S2 fixed point qualitatively: the charge sector couplings reach some fixed value explicitly in \( \lambda_{12}^\rho \) and \( \lambda_{12}^\sigma \), and are marginally irrelevant; the spin sector couplings approach zero from positive values, and are marginally irrelevant. Finally, the “charge-spin” couplings \( w_{12}^\rho \) and \( w_{12}^\sigma \) go to zero, and are irrelevant, which is ensured by the condition \( \Lambda^\rho > 0 \). Indeed, consider small deviations of comparable magnitudes for all couplings and allowing only positive \( \Lambda_{ab} \). Since we have finite \( \Lambda^\rho > 0 \), first the \( w_{12}^\rho \) will renormalize quickly to zero, without affecting significantly the other couplings. Then the \( \lambda_{ab} \) will renormalize to zero via slow marginal flows.

D. Numerical studies of the flows

We can solve the RG equations numerically for given initial conditions and check whether the couplings flow into the domain of attraction of the C2S2 fixed point or not. We
The RG flows are qualitatively similar for different points in the same phase, so we only show one representative picture for each case. Figure 2 shows the flows in the C2S2 phase. The scale parameter $\ell$ is the $x$ axis, while logarithm of the couplings is the $y$ axis. In this way, we clearly see that the couplings separate into three groups, which is well explained by the C2S2 fixed point in Sec. II C: the $w_{12}^{\sigma}$ flow to 0 exponentially rapidly, the $\lambda_{ab}^{\sigma}$ flow to 0 marginally slowly, while the $\lambda_{ab}^{\rho}$ saturate.

Figure 3 illustrates the flows in the C1S0 phase. Here we use real values of the coupling as the $y$ axis and only show selected couplings, $\lambda_{11}^{\sigma}$, $\lambda_{22}^{\sigma}$, $w_{12}^{\rho}$, and $w_{12}^{\sigma}$. We clearly see that these couplings diverge (and so do the other couplings not shown in the figure).

E. Examples of phase diagrams with C2S2 metal stabilized by extended interactions

For illustration in our paper, we consider the following interaction potential,

$$V(x-x') = \begin{cases} U, & |x-x'| = 0 \\ \kappa U e^{-\gamma|x-x'|}, & |x-x'| \geq 1 \end{cases}. \tag{32}$$

Here $U$ is the overall energy scale and also the on-site repulsion. The relative magnitude of the extended repulsion is set by some factor $\kappa < 1$. Beyond one lattice spacing, the potential decreases exponentially with decay rate $\gamma$. For $\gamma \rightarrow \infty$, we obtain the Hubbard model with on-site interaction only, while for small $\gamma$ the interaction extends over many lattice sites.

We also consider the above potential but truncated at the fourth neighbor. This tests robustness of our conclusions to modifications where the interactions have finite but still somewhat extended range, as may be preferable in numerical studies of such electronic models.

I. Weak coupling phase diagram for potential [Eq. (32)]

The extended repulsion, Eq. (32), is in Fourier space,

$$V_{Q} = U \left[ 1 - \kappa + \frac{\kappa \sinh(\gamma)}{\cosh(\gamma) - \cos(Q)} \right]. \tag{33}$$

For given model parameters, we use Eqs. (11)–(18) to set initial conditions. We follow the RG flows and identify the phases as described above, thus mapping out the “weak coupling phase diagram.” Here and in the rest of the paper, we take $\kappa=0.5$. This is loosely motivated by the recent ab initio...
The noninteracting problem has one band for $t_2/t_1 < 0.5$ and two bands for $t_2/t_1 > 0.5$, cf. Figure 1, and we focus on the latter region. The limit $\gamma \to \infty$ corresponds to the Hubbard model with on-site repulsion only, and the C2S2 phase is stable only over a narrow window $t_2/t_1 \in [0.5 \cdots 0.57]$ (Refs. 18 and 23). The C2S2 region becomes progressively wider as we increase the interaction range $1/\gamma$.

The limit $\gamma \to 0$ corresponds to the Hubbard model with on-site repulsion only, and the C2S2 phase is stable only over a narrow window $t_2/t_1 = 0.57$, cf. Figure 1, and we focus on the latter region.

We can understand this qualitatively as follows. For fixed band parameters, when $\gamma \to 0$ the values of $V_Q$ for all nonzero $Q$ approach $U(1-\kappa)$, while $V_{Q=0} = 2\kappa U/\gamma$ continues to increase. The corresponding contribution to $\Lambda^\rho$ is

$$\delta \Lambda^\rho = \frac{V_{Q=0}}{2\pi} \left[ \frac{1}{v_1} \frac{1}{v_2} - \frac{4}{v_1 + v_2} \right] = \frac{V_{Q=0}}{2\pi} \left[ \frac{(v_1 - v_2)^2}{v_1 v_2 (v_1 + v_2)} \right].$$

(34)

which is positive for any $v_1 \neq v_2$ and grows with increasing $V_{Q=0}$. Note also from Eqs. (11)-(18) that the $V_{Q=0}$ enters only in the $\lambda^\rho_{ab}$ couplings. Large bare value of $\Lambda^\rho$ makes the $w_{12}^\rho_{\sigma}$ flows strongly irrelevant. Their effect on the $\lambda^\rho_{ab}$ flows is rapidly decreasing and expires. The $\lambda^\rho_{ab}$ couplings start repulsive and stay so and eventually flow to zero via marginal flows. This argument is strictly true in the small $\gamma$ limit, while for finite $\gamma$ the interplay of different flows is more complex and requires numerical study as done in Fig. 4.

2. Weak coupling phase diagram for potential [Eq. (32)] truncated at the fourth neighbor

Here, we truncate the interaction at the fourth neighbor, so the Fourier transform is,

$$V_Q = U \left[ 1 + 2\kappa \sum_{m=1}^{4} e^{-\gamma \cos(nQ)} \right].$$

The phase diagram in the weak coupling RG approach is shown in Fig. 5. We see that unlike the case without the truncation, the C1S0 phase opens again as $\gamma \to 0$. Since we only include up to the fourth neighbor interaction, $V_{Q=0}$ does not dominate over $V_{Q \neq 0}$ even in the $\gamma \to 0$ limit. For $\kappa = 0.5$ and $\gamma = 0$, there is significant structure in $V_Q$ including sign changes as a function of $Q$, which can make bare spin couplings $\lambda^\rho_{ab} \sim V_{2x\mu}$ to be marginally relevant. Nevertheless, for intermediate $\gamma$ there is still a wide window of the C2S2 phase.

III. WEAK TO INTERMEDIATE COUPLING: PHASES OUT OF C2S2 UPON INCREASING INTERACTION

A. Harmonic description of the C2S2 phase

Let us begin with a harmonic description of the C2S2 metal. Technical steps and many details of the bosonization essentially follow Ref. 14 and references therein. We write

$$c_{Pa \sigma} = \eta_{a \sigma} e^{i(x_{a \sigma} + \alpha_{a \sigma})},$$

where $\varphi$ and $\theta$ are canonically conjugate boson fields and $\eta$ are Klein factors.

We define “charge” and “spin” boson fields,

$$\theta_{\rho \rho' \sigma} = \frac{1}{\sqrt{2}} (\theta_{a \sigma} \pm \theta_{\bar{a} \sigma}'),$$

(36)

and “even” and “odd” flavor combinations,

$$\theta_{\mu \mu'} = \frac{1}{\sqrt{2}} (\theta_{1 \mu} \pm \theta_{2 \mu'}),$$

(37)

with $\mu = \rho, \sigma$. Similar definitions hold for the $\varphi$ fields.

We can now bosonize all four-fermion interactions [Eqs. (7)-(10)]. First consider the spin sector. The $C^\rho_{ab}$ terms give velocity renormalizations, while the $\lambda^a_{ab}$ terms are written out in Sec. IVA of Ref. 14 and are not repeated here. We assume
that the $\lambda_{\alpha\beta}^\rho$ are marginally irrelevant in the C2S2 phase. The fixed-point Lagrangian has effectively decoupled boson fields $\theta_{\rho \sigma}$ and $\theta_{\sigma \rho}$ with Luttinger parameters $g_{1\sigma}=g_{2\sigma}=1$, dictated by SU(2) spin rotation invariance.

The Lagrangian in the charge sector is

$$L^g = \frac{1}{2\pi} \left[ \partial_i \Theta^T \cdot A \cdot \partial_i \Theta + \partial_i \Phi^T \cdot B \cdot \partial_i \Phi \right] + \frac{i}{\pi} \partial_i \Theta^T \cdot \partial_i \Phi,$$

where we defined $\Theta^T = (\theta_{\rho \sigma}, \theta_{\sigma \rho})$ and $\Phi^T = (\varphi_{\rho \sigma}, \varphi_{\sigma \rho})$. Matrix elements of $A$ and $B$ are

$$A_{11} = \bar{u} + \frac{\lambda_{11}^\rho + \lambda_{12}^\rho + 2\lambda_{12}^\rho}{2\pi} + \frac{C_{11}^\rho + C_{12}^\rho + 2C_{12}^\rho}{2\pi} = \bar{u} + \frac{V_{2kFx}}{4\pi} - \frac{V_{2kFx}}{2\pi} + \frac{V_{4}}{2\pi} - \frac{U}{2\pi},$$

$$A_{22} = \bar{u} + \frac{\lambda_{11}^\rho + \lambda_{12}^\rho - 2\lambda_{12}^\rho}{2\pi} + \frac{C_{11}^\rho + C_{12}^\rho - 2C_{12}^\rho}{2\pi} = \bar{u} - \frac{V_{2kFx}}{4\pi} + \frac{V_{2kFy}}{2\pi} + \frac{V_{4}}{2\pi} - \frac{U}{2\pi},$$

$$A_{12} = A_{21} = \bar{v} - \frac{\lambda_{11}^\rho - \lambda_{12}^\rho}{2\pi} + \frac{C_{11}^\rho - C_{12}^\rho}{2\pi} = \bar{v} - \frac{V_{2kFy}}{4\pi} + \frac{V_{2kFx}}{2\pi},$$

$$B_{11} = \bar{u} - \frac{\lambda_{11}^\rho + \lambda_{12}^\rho + 2\lambda_{12}^\rho}{2\pi} + \frac{C_{11}^\rho + C_{12}^\rho + 2C_{12}^\rho}{2\pi} = \bar{u} + \frac{V_{2kFy}}{4\pi} + \frac{V_{2kFx}}{2\pi} + \frac{V_{4}}{2\pi} - \frac{U}{2\pi},$$

$$B_{22} = \bar{u} - \frac{\lambda_{11}^\rho + \lambda_{12}^\rho - 2\lambda_{12}^\rho}{2\pi} + \frac{C_{11}^\rho + C_{12}^\rho - 2C_{12}^\rho}{2\pi} = \bar{u} + \frac{V_{2kFx}}{4\pi} + \frac{V_{2kFy}}{2\pi} + \frac{V_{4}}{2\pi} - \frac{U}{2\pi},$$

$$B_{12} = B_{21} = \bar{v} - \frac{\lambda_{11}^\rho - \lambda_{12}^\rho}{2\pi} + \frac{C_{11}^\rho - C_{12}^\rho}{2\pi} = \bar{v} + \frac{V_{2kFx}}{4\pi} + \frac{V_{2kFy}}{2\pi} + \frac{V_{4}}{2\pi},$$

where

$$\bar{u} = \frac{u_1 + u_2}{2}, \quad \bar{v} = \frac{u_1 - u_2}{2}.$$
relevant; $\theta_{p}$ gets pinned and we obtain a Mott insulator.

Our intermediate coupling procedure is as follows. Using the harmonic theory of the C2S2 phase, we calculate the scaling dimensions $\Delta[W]$, Eq. (49), and $\Delta[H_8] = \Delta[\cos(4\theta_{p})]$ from the Lagrangian $L^0$, Eq. (38). Details are described in Appendix and calculations are done numerically in the end.

If both $\Delta[W]$ and $\Delta[H_8]$ are larger than 2, the C2S2 metal is stable. As interactions increase, eventually either $W$ or $H_8$ becomes relevant. In general, there are two cases.

1. If $H_8$ becomes relevant first, we pin $\theta_{p}$, and enter C1S2 Mott insulator. To be more precise, we can further qualify the label as “C1[$\rho+$]S2”; the remaining “charge” mode “$\rho$−” represents local current loop fluctuations and does not conduct. This is the spin liquid phase called spin Bose-metal in Ref. 14 and described in detail there. Exploring conditions for finding such phase in electronic models is our main goal here.

2. On the other hand, if the $W$ term becomes relevant first, we enter C1S0 conducting state with a spin gap $A_1$. If $H_8$ becomes relevant first, we pin $A_1$, and we obtain fully gapped Mott insulator C0S0, which is likely the same period-2 valence bond solid (VBS). This connects to dimerized phase in the $J_1$−$J_2$ spin chain appropriate in the strong interaction limit of the electron system.

1. Instability out of C1[$\rho+$]S2 driven by spin-charge coupling $W$

In the present analysis focusing on the $p+$ and $\rho−$ fields, we can also crudely estimate the extent of the C1S2 or C1S0 phases once either happens out of the C2S2. Suppose the umklapp $H_8$ is relevant first and we are in the C1S2 phase. We still need to remember the $W$ term since it can become relevant if we continue increasing the interaction strength. To estimate the scaling dimension of the $W$ term, we assume now that the $\theta_{p}$ field is massive and integrate out $\theta_{p}$ and $\varphi_{p}$. Mathematically this amounts to sending $A_{11} \to \infty$, and we obtain

$$\Delta[W; \theta_{p}] = \left[ \frac{A_{22}B_{11}}{B_{11}B_{22} - B_{12}^2} \right]^{1/2} + 1. \quad (51)$$

This assumption is approximate but reasonable, since once the parameters are such that the system is in the C1S2 phase, the relevant $H_8$ will grow and quickly stiffen the $A_{11}$ in positive feedback loop.

The C1S2 phase is stable if $\Delta[W] > 2$, and this analysis is similar to the stability analysis of the SBM in Ref. 14. If $\Delta[W]$ drops below 2, the $W$ term becomes relevant and the $\varphi_{p}$ field will be pinned, together with gapping out the spin sector, cf. Eq. (48). The final result is some “C0S0” phase, whose precise character depends on the details of the couplings $w_{ij}^\rho$. This is studied in Sec. IVB of Ref. 14. For the present repulsive electron model, we have $w_{12}^\rho, w_{12}^\varphi > 0$, so the resulting C0S0 is likely a period-2 valence bond solid (VBS). This connects to dimerized phase in the $J_1$−$J_2$ spin chain appropriate in the strong interaction limit of the electron system.

2. Instability out of C1[$\rho+$]S0 driven by umklapp $H_8$

Suppose now the $W$ interaction becomes relevant first. From Eq. (48), it is natural that $\varphi_{p}$ is pinned, the spin sector gets gapped, and we are in C1S0 phase. Here we postulate mass for $\varphi_{p}$ (essentially sending $B_{12} \to \infty$) and calculate the effective scaling dimension of the umklapp term,

$$\Delta[H_8; \varphi_{p}] = \left[ \frac{B_{11}A_{22}}{A_{11}A_{22}} \right]^{1/2}. \quad (52)$$

If $\Delta[H_8] > 2$, the C1S0 is stable. Once $\Delta[H_8]$ drops below 2, the overall charge mode $\theta_{p}$ is pinned and we obtain fully gapped Mott insulator C0S0, which is likely the same period-2 VBS discussed earlier.

C. Numerical results

We consider the same models with extended density-density interactions as in the weak coupling analysis in Sec. II E, parking ourselves initially in the C2S2 phase in Figs. 4 and 5. From the preceding discussion, we can obtain two phases out of the C2S2 upon increasing interaction strength—either C1[$\rho+$]S0 or C1[$\rho−$]S2. To visualize the results, we imagine adding the overall interaction strength $V$ as the $z$-axis to Figs. 4 and 5. We then project down which results are obtained in the intermediate coupling procedure as explained in the text. White region is C1S0 at weak coupling, cf. Fig. 4, and is not considered here.

![FIG. 6. (Color online) Projection of phases out of the C2S2 of Fig. 4 as we increase overall repulsion strength $V$, which we imagine to be the $z$ axis perpendicular to the page (Fig. 7 gives one cut at $y=0.4$ with such $V$ axis shown explicitly). The results are obtained in the intermediate coupling procedure as explained in the text. White region is C1S0 at weak coupling, cf. Fig. 4, and is not considered here.](attachment:045105-7.png)
We see that the \( U \) only contributes to \( A_{11} \). This monotonically “stiffens” the \( \theta_{\sigma} \) (lowering \( \Delta[H] \)) but “softens” the \( \varphi_{\rho} \) (increasing \( \Delta[W] \)). Therefore we only expect the C1S2 phase out of the C2S2 as found in the numerical calculations.

On the other hand, for small \( \gamma \) we can see from Eq. (33) that \( V_{Q=0} \) will dominate over \( V_{Q\neq0} \). Keeping only \( V_{Q=0} \), the matrices \( \mathbf{A} \) and \( \mathbf{B} \) become

\[
\mathbf{A} = \left( \begin{array}{c} \bar{v} + \frac{2U}{\pi} v_r \\ v_r \end{array} \right), \quad \mathbf{B} = \left( \begin{array}{c} \bar{v} v_r \\ v_r \bar{v} \end{array} \right).
\]

Thus the small \( \gamma \) case has similar mathematical structure to the large \( \gamma \) case. The physical difference is that here the transition to the C1S2 is driven by the \( V_{Q=0} \) instead of the on-site Hubbard \( U \). Note also that since \( V_{Q=0} = 2kU/\gamma \) for \( \gamma \ll 1 \), the transition requires only small values of \( U \), which is why we can ignore all \( V_{Q\neq0} \) compared to the band velocities.

Now we consider a cut at \( \gamma = 0.4 \) to see more details in the \( t_2/t_1 - V \) plane. The results are shown in Fig. 7. Compared with the two limits \( \gamma \gg 1 \) and \( \gamma \ll 1 \) above, all possibilities that we discussed out of the C2S2 are realized here. The C1S0 phase appears for \( t_2/t_1 < 0.65 \) for some quantitative reasons. Various \( V_Q \) are all of the same order, unlike the \( \gamma \ll 1 \) case. At the same time, they have some nontrivial \( Q \)-dependence, unlike the \( \gamma \gg 1 \) case, which is somehow enough to make the \( W \) term become relevant and preempt the umklapp term. Note that for small interactions the scaling dimension of the \( W \) term can be obtained from the weak coupling RG equations for the \( \nu^{0+\sigma} \) in Sec. II B by setting all \( \lambda_{ab} = 0 \) (since we ignore the spin sector in the present procedure). Thus, \( \Delta[W] = 2 + \lambda^\sigma \), where \( \lambda^\sigma \) is defined in Eq. (31).

Since \( \lambda^\sigma \) can only decrease under the weak coupling RG and the shaded C2S2 region in Fig. 4 was found to be stable, we expect \( \Delta[W] \) here to increase with \( V \) for small \( V \), in agreement with numerical calculations. However, we find that \( \Delta[W] \) eventually starts to decrease with increasing \( V \) and can become relevant before the umklapp. This is a quantitative matter and comes from putting together all interactions \( H_{\rho L}^\sigma \) and \( H_{\rho\text{chiral}} \), Eqs. (7)-(9), in the intermediate coupling procedure. Such numerical calculations give us that the C2S2 can exit into the C1S0 phase. For larger \( t_2/t_1 > 0.65 \) in Fig. 7, we obtain the sought for C1S2 spin liquid phase.

This concludes the presentation of formal results within the particular procedure for intermediate scale analysis. Let us now think how to combine the weak and intermediate coupling approaches more realistically and see where our results are more robust.

First of all, in the weak coupling analysis the C2S2 phase is unstable beyond the shaded regions in Figs. 4 and 5. However, this is lost in the specific intermediate coupling procedure, which, when applied for small coupling, would give C2S2 essentially everywhere. For example, in Fig. 7 we see monotonic growth of the C2S2 phase with \( t_2/t_1 \) past the point where the weak coupling analysis predicts instability. The reason for this discrepancy is the complete neglect of the spin sector in the formal intermediate scale procedure. Indeed, in the weak coupling analysis, the instabilities manifest dramatically once one of the \( \lambda_{\rho\sigma} \) becomes negative, causing runaway flows. This can happen even when the bare \( \lambda_{\rho\sigma} \) are repulsive because they are renormalized downwards and can be driven negative by the \( w_{12}^{\rho\sigma} \) contributions in Eqs. (26) and (27), where we assume \( w_{12}^{\rho\sigma} w_{12}^{\rho\sigma} \). Also, the \( \lambda^\sigma \) couplings feed back into the flow of \( w_{12}^{\rho\sigma} \), so the RG flow behavior is even more complex. So far we have dealt with this inadequacy of the intermediate scale procedure by simply cutting
towards the right boundary. This discrepancy arises because our intermediate coupling procedure completely ignores the spin sector. More realistically, we expect the C2S2 phase to peak somewhere in the middle of the range shown in Fig. 7 and become bounded by the C1S0 for larger \( t_2/t_1 \). Similar considerations apply to the C1S2 phase, which is bounded by the C0S0.

We can also discuss our earlier reservation about using bare values of the couplings instead of some renormalized values. Thinking about some RG treatment, we expect that the extent of the C2S2 phase is larger and also the part of the C2S2 phase exits into the C1S2 spin liquid upon increasing interactions, and our results are probably more robust near \( \gamma \sim 0.2 \)–0.3 where the C2S2 has the largest extent along the \( t_2/t_1 \) axis.

IV. SUMMARY AND DISCUSSION

To summarize, in this paper we consider electronic models for realizing spin Bose-metal (spin liquid) phase on the two-leg triangular strip found in Ref. 14 in spin-1/2 model with ring exchanges. We identify the SBM with the C1S2 Mott insulator of electrons.

In Sec. II, we start with a two-band electron system, which is C2S2. Instead of considering only the on-site Hubbard-type repulsion, we study generally longer-ranged density-density repulsion. This is motivated in part by the expectation that real Coulomb interaction is not screened in Mott insulator materials, so further neighbor repulsion can be significant, as brought up by recent ab initio work for the spin liquid material \( \kappa-(ET)_2Cu_2(CN)_3 \). Using weak coupling RG analysis for the zigzag chain problem, we find that such extended interactions open much wider window of the C2S2 metal compared with the Hubbard model. The main results are shown in Figs. 4 and 5. In the first figure, we have essentially an independent control over the velocity repulsion \( V_{q=0} \) as the main stabilizing force for the metal. In the second figure, we truncate interactions at the fourth neighbor to...
check the robustness of our conclusions, in view that such models may be easier to explore using numerical DMRG. Our detailed quasi-1D considerations agree with the intuition that in real metals electronic pairing instabilities are suppressed by the long-ranged piece of the Coulomb interaction. Such widening of the C2S2 region by extending the model interaction range is warranted if we want to bring the electronic ladder system closer to realistic situations in the 2D candidate spin liquid materials.

In Sec. III, we begin with stable C2S2 metal at weak coupling and use bosonization to extend the analysis to intermediate coupling by gradually increasing the overall repulsion strength. Within effective bosonic theory, we identify potential instabilities of the C2S2 phase to spin-charge interaction $W$ [Eq. (48)] and umklapp interaction $H_8$ [Eq. (50)]. The $W$ can drive the system into $C1[p+]S0$ phase with spin gap but still conducting along the chain, while the umklapp $H_8$ can produce $C1[p−]S2$ Mott insulator with three gapless modes, which is the desired SBM phase. We calculate the scaling dimensions of the $W$ and $H_8$ terms in the harmonic theory of the C2S2 metal using bare couplings in the charge sector and assuming stability in the spin sector—this constitutes our naive intermediate coupling procedure. The calculation of scaling dimensions is described in Appendix and is done numerically in the end.

We consider two cases depending on which of the terms $W$ or $H_8$ becomes relevant first and apply similar intermediate coupling approach inside the resulting phase. Assuming strong field pinning by the already relevant term, we calculate the scaling dimension of the remaining term and estimate when it eventually drives the system into fully gapped C0S0 paramagnet (which is likely connected to the dimerized phase of the $J_1−J_2$ Heisenberg model at strong coupling). With the help of such admittedly crude analysis, we can map out the phase diagram in weak to intermediate coupling regime as illustrated in schematic Fig. 8 (based on more naive Fig. 7). Figures 6 and 9 summarize our results and show where the C2S2 metal goes to the C1S2 (SBM spin liquid) upon increasing overall repulsion strength. We conclude that the C1S2 phase is quite natural out of the wider C2S2 metallic region, in particular when driven by extended repulsive interactions. It would be very interesting to confront our theoretical predictions with numerical DMRG studies of such electronic models with extended repulsion.

So far, we have approached the intermediate coupling Mott insulator from the weak coupling metallic side. One could try to attack the same problem starting from the strong coupling limit deep in the Mott insulator where Heisenberg spin-1/2 model is appropriate. As one nears the metallic phase, it becomes important to include multiple spin exchanges in the effective spin Hamiltonian to better capture charge fluctuations in the underlying electron system.\(^7,15,16,30\) This is the motivation behind Ref. 14 studying $J_1−J_2$ chain with additional four-spin ring exchanges. The concept study Ref. 14 allowed arbitrary variation in the ring coupling compared with the Heisenberg couplings. However, coming from an electronic model these do not vary independently and more exchange terms are also generated. It would be interesting to pursue such approach systematically studying effective spin models with multispin exchanges for realistic electronic models to see if they harbor the SBM phase. We do not make such attempts here, but only give few simple observations on how the derivation of the spin model is modified in the presence of extended repulsion.

First of all, for the two spin exchanges, the familiar Hubbard model expression $J_{rr'}=4r^2_{rr'}/U$ is modified to $J_{rr'}=4r^2_{rr'}/(V_0−V_{r−r'})$. The energy denominator is not simply the on-site $U=V_0$ but also includes interaction potential between the two sites $r$ and $r'$. For example, Ref. 25 estimates $V_1/V_0=0.43$ for the $\kappa$-(ET)$_2$Cu$_2$(CN)$_3$ spin liquid material, and this would significantly affect values of the exchange constants. Energy denominators for all virtual processes are similarly affected and take a form of a charging energy for the deviations from the background. Multispin exchange amplitudes are given by a product of electron tunneling amplitudes for a given virtual path divided by a product of such charging energies in intermediate states along the path. Thus, the multispin exchanges may in fact be relatively more important in systems with extended interactions.

As an extreme example, imagine a very slow decrease in $V(r−r')$ up to some distance $R$ (and perhaps a faster drop thereafter). Then all exchange loops up to such radius $R$ will have large amplitudes. The multispin exchanges encode the underlying kinetic energy of electrons, and our intuition is that this would like to retain some itinerancy in the spin degrees of freedom even when the charges are localized. From such strong to intermediate coupling perspective, it appears that extended interactions would tend to stabilize the SBM spin liquid near the insulator-metal transition, similar to our conclusion from the weak to intermediate coupling study in the quasi-1D models in this paper. It would be interesting to pursue such considerations more carefully and in realistic electronic models. We hope that our work will further stimulate numerical studies of such models on ladders and in two dimensions.

**ACKNOWLEDGMENTS**

We would like to thank M. P. A. Fisher, I. Gonzalez, R. Melko, and D. N. Sheng for useful discussions and M. P. A. Fisher for stimulating this work and critical reading of the manuscript. This research is supported by the A. P. Sloan Foundation and the National Science Foundation through Grant No. DMR-0907145.

**APPENDIX: DERIVATION OF $\Delta[\cos(4\theta_{ps})]$ AND $\Delta[\cos(2\varphi_{ps})]$ IN C2S2 PHASE**

Equation (38) gives quadratic Lagrangian for the charge sector. First, we redefine the fields which still satisfy the same commutation relations,

$$\Theta = S \cdot \Theta_1, \quad \Phi = S \cdot \Phi_1.$$  \hspace{1cm} (A1)

Here $S$ is an orthogonal $2 \times 2$ matrix diagonalizing the matrix $A$,

$$S^T \cdot A \cdot S = \begin{pmatrix} A_1 & 0 \\ 0 & A_2 \end{pmatrix} = A_D.$$  \hspace{1cm} (A2)

The Lagrangian becomes
Define another set of conjugate fields,
\[
\Theta_1 = \frac{1}{\sqrt{A_D}} \cdot \Theta_2, \quad \Phi_1 = \sqrt{A_D} \cdot \Phi_2. \tag{A4}
\]

We obtain
\[
\mathcal{L}' = \frac{1}{2\pi} \left[ \partial_\tau \Theta_1^T \cdot A_D \cdot \partial_\tau \Theta_1 + \partial_\tau \Phi_1^T \cdot B' \cdot \partial_\tau \Phi_1 \right] + \frac{i}{\pi} \partial_\tau \Theta_1^T \cdot \partial_\tau \Phi_1 . \tag{A5}
\]

where
\[
B' = \sqrt{A_D} \cdot S^T \cdot B \cdot S \cdot \sqrt{A_D}. \tag{A6}
\]

We use the same trick to diagonalize matrix \(B'\),
\[
\Theta_2 = R \cdot \Theta_3, \quad \Phi_2 = R \cdot \Phi_3, \tag{A7}
\]

where \(R\) is an orthogonal matrix which satisfies,
\[
R^T \cdot B' \cdot R = \begin{pmatrix} B'_1 & 0 \\ 0 & B'_2 \end{pmatrix} = B''_D. \tag{A8}
\]

The Lagrangian becomes,
\[
\mathcal{L}' = \frac{1}{2\pi} \left[ \partial_\tau \Theta_3^T \cdot A_D \cdot \partial_\tau \Theta_3 + \partial_\tau \Phi_3^T \cdot B''_D \cdot \partial_\tau \Phi_3 \right] + \frac{i}{\pi} \partial_\tau \Theta_3^T \cdot \partial_\tau \Phi_3 . \tag{A9}
\]

Now we can calculate the scaling dimension of \(\cos(4\theta_{\rho\sigma})\) and \(\cos(2\varphi_{\rho\sigma})\) from Eq. (A9) through relations
\[
\Theta = S \cdot \frac{1}{\sqrt{A_D}} \cdot R \cdot \Theta_3, \tag{A10}
\]

and scaling dimensions of the final fields,
\[
\Delta[e^{i\Theta}] = \frac{\sqrt{B''_D}}{4}, \quad \Delta[e^{i\Phi}] = \frac{1}{4\sqrt{B''_D}}, \tag{A12}
\]

where the right hand sides mean corresponding diagonal matrix elements. Therefore, we find general form for the dimensions we are interested in
\[
\Delta[\cos(4\theta_{\rho\sigma})] = 4\sqrt{B''_D} \left( \frac{S_{11} R_{11}}{\sqrt{A_1}} + \frac{S_{12} R_{12}}{\sqrt{A_2}} \right)^2 + 4\sqrt{B''_D} \left( \frac{S_{21} R_{21}}{\sqrt{A_1}} + \frac{S_{22} R_{22}}{\sqrt{A_2}} \right)^2, \tag{A13}
\]

\[
\Delta[\cos(2\varphi_{\rho\sigma})] = \frac{(\sqrt{A_1} S_{21} R_{11} + \sqrt{A_2} S_{22} R_{21})^2}{\sqrt{B''_D}} + \frac{(\sqrt{A_1} S_{21} R_{21} + \sqrt{A_2} S_{22} R_{22})^2}{\sqrt{B''_D}}, \tag{A14}
\]

where \(S_{ab}\) and \(R_{ab}\) are matrix elements of \(S\) and \(R\).