I. INTRODUCTION

A universal property shared by most known iron-based superconductors (FeSCs) is the bulk coexistence of two or even more distinct long-range orders [1-12], such as superconductivity, stripe-type spin-density-wave (SDW) order, nematic order, and other possible orders. The competition and coexistence of these orders leads to a very complicated global phase diagram [1-12]. Acquiring a detailed knowledge of the phase diagram is an important step towards a better understanding of FeSCs.

Among the long-range orders competing with superconductivity, a particular role is played by the nematic order, induced by an electronic state that spontaneously breaks the $C_4$ (tetragonal) symmetry of the system down to a $C_2$ (orthogonal) symmetry. Extensive experiments have confirmed that nematic order exists in almost all FeSCs [2, 5, 10, 11, 13]. In most cases, the nematic order sets in at a temperature $T_n$ slightly higher than the critical temperature of magnetic order $T_m$ [4, 6, 10, 13, 19].

Usually, the magnetic order is generated by a stripe-type SDW, and possesses two characteristic vectors $Q_X = (\pi, 0)$ and $Q_Y = (0, \pi)$ in the Brillouin zone of the iron square lattice, which relate to the spin operator $S(r)$ in the form $S(r) = M_X e^{iQ_X \cdot r} + M_Y e^{iQ_Y \cdot r}$ [12, 20]. This stripe SDW breaks the discrete lattice rotational symmetry by selecting out only one of the two characteristic vectors $Q_X$ and $Q_Y$, preserving the $C_2$ symmetry [4, 8, 10, 12]. Because the nematic order and SDW order coexist over a large part of the global phase diagram, it is widely believed [4, 8, 12] that the nematic order is actually induced by the fluctuation of magnetic order.

It was unexpected that experiments had found a new type of $C_4$ symmetric magnetic order that preserves the tetragonal symmetry in a number of hole-doped FeSCs, including Ba(Fe$_{1-x}$Mn$_x$)$_2$As$_2$ [21], Ba$_{1-x}$Na$_x$Fe$_2$As$_2$ [22, 23], Sr$_{1-x}$K$_x$Fe$_2$As$_2$ [24], and Ba$_{1-x}$K$_x$Fe$_2$As$_2$ [25-28]. This $C_4$ magnetic state is characterized by biaxial magnetic orders [29, 32], and the corresponding spin operator is given by $S(r) = M_X e^{iQ_X \cdot r} + M_Y e^{iQ_Y \cdot r}$ [33, 34]. It has been suggested that this double-$Q$ magnetic state has two possible realizations [29, 33, 35]: a charge-density wave (CDW) in which $M_X$ and $M_Y$ are collinear; a spin-vortex crystal (SVC) in which $M_X$ and $M_Y$ are orthogonal. Since the largest value of $T_c$ of FeSCs is observed at the proximity of tetragonal $C_4$ magnetic order [22, 26], there might exist a quantum critical point (QCP) at certain doping $x_c$ in the superconducting (SC) dome [33]. After its discovery, the double-$Q$ structured $C_4$ SDW state has stimulated a variety of experimental [21, 22, 24, 27] and theoretical works [24, 31, 37, 39].

In this paper, we consider the effects caused by the competition of superconductivity with both stripe-type $C_2$ symmetric and $C_4$ symmetric magnetic orders in a hole-doped FeSC Ba$_{1-x}$K$_x$Fe$_2$As$_2$. Böhmer et al. [26] have experimentally investigated the global phase diagram of Ba$_{1-x}$K$_x$Fe$_2$As$_2$, and identified five distinct thermodynamically stable ordered phases, which are schematically shown in Fig. 1. One can see that the critical line for the nematic order displays a rather complicated dependence on doping $x$ and temperature $T$: it decreases with growing $x$ at high $T$, bends backwards to lower $x$ slightly above $T_c$, and eventually exhibits a negative slope after penetrating into the SC dome. In the narrow doping region in which the nematic critical line has a positive slope, $T_c$ is moderately suppressed. Close to the putative magnetic QCP, represented by $x_2$ in Fig. 1, there appears on the phase diagram a region that manifests $C_4$ symmetric SDW state, which occupies part of the usual $C_2$ symmetric SDW phase and coexists with superconductivity below $T_c$. In principle, the experimentally observed $C_4$ SDW state might be a CSDW or SVC type state, which needs to be clarified theoretically.

Instead of trying to explain the entire phase diagram observed in Ref. [26], we perform a more moderate task...
II. EFFECTIVE THEORY AND RG ANALYSIS

Many of the basic properties of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ can be described by a three-band model that contains one hole pocket at the center of Brillouin zone $Q_x = (0,0)$ and two electron pockets centered at two specific momenta $Q_X = (\pi,0)$ and $Q_Y = (0,\pi)$ [12, 18–20, 30, 33–35]. The microscopic model is written as [12, 19]

\[ H = \sum_{k,i\in(X,Y,\Gamma)} \varepsilon_{k,i} c_{k\sigma,i}^\dagger c_{k\sigma,i} + H_4, \]  

with the interacting term $H_4$ is given by

\[ H_4 = \sum_{k,i\in(X,Y)} U_3 \left( c_{k\alpha,i}^\dagger c_{k\gamma,i}^\dagger c_{k\delta,i} c_{k\beta,i} + \text{h.c.} \right) \delta_{\alpha\beta} \delta_{\gamma\delta} + \sum_{k,i\in(X,Y)} U_1 c_{k\alpha,i}^\dagger c_{k\gamma,i}^\dagger c_{k\delta,i} c_{k\beta,i} \Gamma \delta_{\alpha\beta} \delta_{\gamma\delta}. \]  

Here, $U_1$ and $U_3$ represent density-density interaction and the pair hoping interaction, respectively. They are responsible for the formation of superconductivity and SDW state [19, 33, 41]. The magnetic structure can be described by two order parameters $M_X$ and $M_Y$, corresponding to the ordering vectors $Q_X = (\pi,0)$ and $Q_Y = (0,\pi)$, which are defined as $M_j = \sum_k c_{k\alpha}^\dagger \varphi_{\alpha\beta} c_{k\beta}, k+Q_{\alpha\beta} \gamma \delta_{\alpha\beta} \delta_{\gamma\delta}$. Both the $C_2$ and $C_4$ symmetric magnetic orders are modeled by the following Ginzburg-Landau free energy [33, 44]

\[ f[M_X, M_Y] = a_m(M_X^2 + M_Y^2) + \frac{w}{2}(M_X^2 + M_Y^2)^2 - \frac{g}{2}(M_X^2 - M_Y^2)^2 + 2w(M_X \cdot M_Y)^2. \]

As illustrated in Ref. [33], the term $2w(M_X \cdot M_Y)^2$ can be rewritten by using an identity:

\[ (M_X \cdot M_Y)^2 = \frac{1}{4}(M_X^2 + M_Y^2)^2 - \frac{1}{4}(M_X^2 - M_Y^2)^2 - (M_X \times M_Y)^2. \]  

Upon carrying out a Hubbard-Stratonovich transformation followed by an integration over all the fermionic degrees of freedom, one can obtain an effective field theory
for the interplay of SDW magnetic and SC orders in the vicinity of magnetic QCP:

\[ \mathcal{L} = \frac{1}{2}(\partial_\mu M_X)^2 + \frac{1}{2}(\partial_\mu M_Y)^2 + a_m (M_X^2 + M_Y^2) \\
+ \frac{(u + w)}{2} \left( M_X^2 + M_Y^2 \right)^2 - \frac{(u - w)}{2} \left( M_X^2 - M_Y^2 \right)^2 \\
+ \partial_\mu \Delta \partial_\nu \Delta + a_s \Delta^2(k) + \frac{u_s}{2} \Delta^2(k) + \frac{\varphi^2}{2w} + \mathcal{L}_A \\
- 2\varphi M_X M_Y + \lambda (M_X^2 + M_Y^2) \Delta^2 + \lambda_{DA} \Delta^2 A^2, \quad (4) \]

where \( \Delta \) is the SC order parameter. Here we use a positive parameter \( \lambda \) to characterize the repulsive interaction (competition) between SC and magnetic orders. In order to evaluate the superfluid density, we have introduced a gauge potential \( A \) via the standard minimal coupling \[33, 34\] with \( \mathcal{L}_A = -\frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 \). This model contains eight fundamental parameters \( a_m, \alpha_s, u_s, w, u, g, \lambda, \) and \( \lambda_{DA} \), which are constants at the mean-field level, but all become cutoff dependent due to interactions.

The transition lines for SDW and SC orders are determined by taking \( a_m = 0 \) and \( a_s = 0 \) respectively. For \( s^+ \)-wave superconductors, we employ the relationship \( \Delta_{F} = -\sqrt{2} \Delta_{XY} = \Delta \) \[8, 12, 19\]. An Ising-type nematic order is induced by the magnetic order, and represented by a term of the form \( M_X^2 - M_Y^2 \) \[8, 12, 18\]. The property of \( C_4 \) magnetic order is determined by the parameter \( w \). In the SC dome, the SC order parameter develops a nonzero mean value, i.e., \( \langle \Delta \rangle = V_0 = -a_s/u_s \) near the magnetic QCP \( x_2 \).

The effective model \[41\] displays different states when the model parameters take various values \[33, 34\]. (i) If \( g < 0 \) and \( w = 0 \), the effective model is in paramagnetic (PM) phase; (ii) The case of \( g > max(0, -w) \) corresponds to the \( C_2 \) SDW phase (with nematic order); (iii) The \( C_4 \) symmetric magnetic state is of SVC-type if \( g < 0 \) and \( w > 0 \), and CSDW-type if \( g < -w \) and \( w < 0 \). Once some of these parameters are altered by external forces, such as doping, magnetic field, and pressure, the system would undergo transitions between distinct phases. However, the quantum fluctuations of order parameters and the interaction between different order parameters can also lead to remarkable changes of model parameters, and as such drive phase transitions. In the next section, we will study the RG flows of these parameters and examine how they are influenced by order parameter fluctuation and ordering competition. The main results are schematically illuminated in Fig. 1 and the detailed derivations and discussions are given in the following.

To proceed, we perform a RG analysis of the effective theory \[41\]. Our focus is on the behavior of the system at low \( T \) and in the vicinity of magnetic QCP. Within this region, the quantum fluctuations of SC order parameter can result in drastic effects even in the SC phase. For the complex SC order parameter \( \Delta (r) \), there are two sorts of fluctuations \[40, 53\], namely the phase fluctuation and amplitude fluctuation. The former fluctuation is gapless and corresponds to the Nambu-Goldstone mode induced by continuous gauge symmetry breaking. This mode does not play any role in the SC state because it is absorbed by the vector gauge boson via the Anderson-Higgs mechanism. The latter one, known as Higgs mode in a locally gauge invariant superconductor, is found by both theoretical and experimental works to result in observable effects \[40, 53\], and hence should be seriously considered \[54, 55\]. In order to capture the quantum fluctuation of SC order parameter around its mean value \( \langle \Delta \rangle \), we define two new fields \( h \) and \( \eta \) by \[54, 55\]

\[ \Delta = V_0 + \frac{1}{\sqrt{2}} (h + i\eta), \quad (5) \]

where \( \langle h \rangle = \langle \eta \rangle = 0 \). The fields \( h \) and \( \eta \) stand for the Higgs mode and Nambu-Goldstone mode, respectively. We substitute Eq. (5) into the effective Lagrangian density \( \mathcal{L} \) \[41\], and obtain the following new effective Lagrangian density:

\[ \mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu M_X)^2 + \alpha_X M_X^4 + \frac{\beta_X}{2} M_X^4 + \frac{1}{2}(\partial_\mu M_Y)^2 + \alpha_Y M_Y^4 + \frac{\beta_Y}{2} M_Y^4 + \frac{1}{2}(\partial_\mu h)^2 + \alpha_h h^2 + \frac{\beta_h}{2} h^4 + \gamma_h h^3 \\
+ \left( \mathcal{L}_A + \frac{\alpha_A}{2} A^2 \right) + \alpha_\varphi \varphi^2 + \gamma_{\varphi XY} \varphi M_X M_Y + \gamma_{\varphi X^2 h} M_X^2 h + \gamma_{\varphi Y^2 h} M_Y^2 h + \gamma_{\alpha A} h^2 A^2 + \lambda_{XY} M_X^2 h^2 + \lambda_{YY} M_Y^2 h^2 + \lambda_{XY} M_X^2 M_Y^2 + \lambda_{hA} h^2 A^2. \quad (6) \]

The gapless Nambu-Goldstone model \( \eta \) naturally disappears after invoking the Anderson-Higgs mechanism. However, the Higgs mode \( h \) remains in the above effective model, and couple directly to the magnetic order parameters \( M_X, M_Y \) and also to vector potential \( A \). The originally massless gauge field \( A \) acquires a finite mass \( \alpha_A \) after absorbing \( \eta \). Moreover, in the above Lagrangian density we have introduced a number of new parameters that are related to the model parameters defined in \[33, 34\] by the following relations:

\[ \begin{align*}
\alpha_X = \alpha_Y &\equiv a_m - \frac{\lambda_{\alpha \alpha}}{u_s}, \quad \alpha_A \equiv -\frac{2\lambda_{\Delta \alpha \alpha}}{u_s}, \quad \alpha_h \equiv -a_s, \quad \alpha_\varphi \equiv \frac{1}{2w}, \quad \beta_X = \beta_Y \equiv u - g, \quad \beta_h \equiv \frac{w}{4}, \\
\gamma_h &\equiv \sqrt{-2a_s u_s} \frac{w}{2}, \quad \gamma_{\varphi XY} \equiv -2, \quad \gamma_{\varphi X^2 h} \equiv 2, \quad \gamma_{\varphi Y^2 h} \equiv 2, \quad \gamma_{\alpha A} \equiv \sqrt{-2a_s u_s}, \\
\lambda_{XY} &\equiv u + g + 2w, \quad \lambda_{hA} \equiv \frac{\lambda_{\alpha A}}{2}, \quad \lambda_{XY} \equiv \frac{\lambda_{\alpha A}}{2}, \quad \lambda_{XY} \equiv \frac{\lambda_{\alpha A}}{2}.
\end{align*} \quad (7) \]
Using these relations, we can derive the flow equations of fundamental parameters by calculating the effective parameters \( \alpha_x, \alpha_y, \alpha_z, \beta_x, \beta_y, \lambda_{XY}, \lambda_{Xh}, \) and \( \lambda_{hA}. \) By performing perturbative expansion in powers of small coupling parameters (50) and utilizing \( \dot{u} \) to denote the derivative of \( u \) with respect to the varying length scale \( l, \) we arrive at the following flow equations with the help of the identities given by Eq. (7) (52):

\[
\dot{a}_m = 2 \left( a_m \frac{\lambda_{Xh}}{u_s} \right) + \frac{1}{4 \pi^2} \left\{ \frac{\lambda}{(1 + 2a_s)} + \frac{8\lambda^2 a_s^2}{u_s^3} + \left[ 1 - 2 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) \right] \left[ 2(2u - g) + \frac{4\lambda^2 a_s}{u_s} \right] \right\} + \frac{\lambda}{u_s} \dot{u} + \frac{\lambda_{Xh}}{u_s^2} \dot{u}_s - \frac{\lambda}{u_s} \left( \frac{\lambda_{Xh}}{u_s} \right),
\]

\[
\dot{a}_s = 2u_s - \frac{1}{2 \pi^2} \left\{ \frac{27a_s}{u_s^3} \left[ 1 - 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) \right] + 3\lambda \left[ 1 - 2 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) \right] \right\} + \frac{9u_s}{4} \left( 1 + 2a_s + 3\lambda_{Xh} \left[ 1 - 2 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) \right] \right)
\]

\[
\dot{u}_s = u_s + \frac{1}{\pi} \left\{ \frac{9a_s^2}{4} \left( 4a_s + 1 \right) + 2\lambda^2 \left[ 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 1 \right] + 54a_s^2u_s^2 \left( 1 + 6a_s \right) - \frac{4\lambda^2}{3} \frac{a_s}{u_s} \left( 4a_s \lambda_{Xh} + 1 \right) \right\} + \frac{27a_s}{u_s^3} \left( 1 + 6a_s \lambda_{Xh} \right),
\]

\[
\dot{u} = u + w + \frac{1}{\pi^2} \left\{ \left[ 9(u-g)^2 + 3(u+g+2w)(u-g) + 5(u+g+2w)^2 + 12u(u-g) \right] \left[ 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 1 \right] \right. \\
\left. - \frac{3\lambda^2}{u_s^3} \left[ 4a_s + 1 \right] + \frac{24a_s\lambda^2(u-g)}{u_s} \left[ 1 - 2 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - a_s \right] + 4w(u+g+2w) \left[ 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 1 \right] \right\} w,
\]

\[
g = g + w - \frac{1}{\pi^2} \left\{ \left[ 9(u-g)^2 - 3(u+g+2w)(u-g) - 3(u+g+2w)^2 - 12u(u-g) \right] \left[ 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 1 \right] \right. \\
\left. - \frac{\lambda^2}{u_s^3} \left[ 4a_s + 1 \right] + \frac{24a_s\lambda^2(u-g)}{u_s} \left[ 1 - 2 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - a_s \right] + 4w(u+g+2w) \left[ 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 1 \right] \right\} w,
\]

\[
\dot{\lambda} = \lambda + \frac{1}{\pi} \left\{ \frac{4\lambda^3}{u_s^3} \left[ 1 - 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) + 2a_s \right] + \lambda (2u - g + 3w) \left[ 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 1 \right] \right. \\
\left. + \frac{16a_s\lambda^2(2u-g+w)}{u_s} \left[ 1 - 2 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) - 2a_s - 1 \right] + 9a_s u_s \lambda (1 + 6a_s) \right\},
\]

\[
\dot{\lambda}_{Xh} = \lambda_{Xh} + \frac{1}{3\pi^2} \left\{ 27a_s u_s \lambda_{Xh} (1 + 6a_s) + \frac{4\lambda_{Xh}(16a_s \lambda_{Xh} + 3u_s)}{u_s} \left[ 1 + 2a_s \left( 1 + \frac{\lambda_{Xh}}{u_s} \right) \right] \right. \\
\left. - \frac{9u_s}{8} \frac{\lambda_{Xh}}{u_s} \left( 4a_s + 1 \right) + 36a_s \lambda_{Xh}^2 \left[ 2 + \frac{\lambda_{Xh}}{u_s} \right] \right\},
\]

\[
\dot{w} = \frac{w}{u_s} \left[ 1 - 4 \left( a_m - \frac{\lambda_{Xh}}{u_s} \right) \right].
\]

III. COMPARISON WITH EXPERIMENTS

In this section, we will compare the RG results with recent experiments. We first numerically solve the self-consistently coupled RG equations, and then manage to understand a number of important features observed by Böhmer et al. in Ba_{1-x}K_xFe_2As_2 (24). We are particularly interested in the doping dependence of nematic critical line in the SC dome, the suppression of superconductivity observed at the magnetic QCP, and the nature of the observed \( C_4 \) symmetric magnetic order, which will be studied one by one based on the RG solutions.

As can be seen from the phase diagram presented in Fig. 1, the magnetic and SC orders are assumed to coexist over a finite region, with \( x_2 \) being the magnetic QCP. Such a coexistence can be realized if the bare values of model parameters satisfy the constraint (19, 20, 57, 60)

\[
\lambda < \sqrt{u_s[(u + w) - (g + w)]} = \sqrt{u_s(u - g)}.
\]

For simplicity, we will only consider the low-\( T \) region in the close vicinity of the magnetic QCP inside the SC dome. In addition, the external field \( A \) is assumed to be weak, but the basic conclusion does not depend on this assumption.
A. Slope of nematic critical line in SC dome

The nematic line is not shown apparently in Fig. 1. However, the $C_2$ magnetic phase is always accompanied (even preempted) by a nematic phase with a critical temperature $T_n$ higher than that of $C_2$ magnetic order \cite{8, 10, 13}. Hence $T_{n4}$ is also a nematic critical line.

A known fact is that a long-range order can always be destroyed by thermal fluctuation at sufficiently high $T$. In a system containing two or more distinct orders, the competition between these orders might destroy some specific order at very low $T$. As a result, the critical line on the $(x, T)$ phase diagram for this specific order has a positive slope in the low-$T$ region, which is often called back-bending behavior. Interestingly, such back-bending behavior has been observed in some high-$T_c$ cuprate superconductor \cite{61–63} and FeSCs \cite{64}. In cuprate Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, a pseudogap exists above $T_c$ on the $(x, T)$ phase diagram. This pseudogap decreases rapidly with growing doping $x$, so its critical line exhibits a negative slope above $T_c$. However, after entering into the SC dome, the critical line for pseudogap was found to bend backwards to lower doping, and thus displays a positive slope in the low-$T$ region \cite{61–63}. A similar behavior was also observed in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ by Nandi et al. \cite{64}. In this case, it is the nematic order that is in strong competition with SC order. The nematic critical line has a negative slope on $(x, T)$ phase diagram above $T_c$, but displays a positive slope below $T_c$ \cite{64}. A common feature observed in these two compounds is that the critical line for the order competing with superconductivity has a positive slope in the low-$T$ region. While a convincing theoretic explanation for the back-bending of pseudogap critical line in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ is lacking, a recent RG work reproduced the back-bending of nematic critical line by studying the competition between nematic and SC orders in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$. \cite{65}. Different from Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, the nematic critical line has a negative slope in the SC dome of Ba$_{1−x}$K$_x$Fe$_2$As$_2$ \cite{26} despite the presence of ordering competition.

In Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, there is only $C_2$ symmetric magnetic order, induced by a stripe-type SDW state. As discussed in Ref. \cite{19}, the existence of nematic order is tuned by the quadratic term $−g(M^2_x − M^2_y)^2$. The system can stay either in the PM phase, or in one of the $M_x$ and $M_y$ magnetically ordered phases. The former case corresponds to a state in which $g < 0$ and no nematic order exists. In the latter case, $g > 0$ and hence the system exhibits a nematic order. Both of these two possibilities can be realized at low $T$. When the competition between nematic and SC orders is sufficiently strong, it is in principle possible for the nematic order to be suppressed in the low-$T$ region, leading to a positive slope of nematic critical line in the SC dome \cite{65}.

We now use the RG solutions to judge whether the nematic critical line has a positive or negative slope in the SC dome of Ba$_{1−x}$K$_x$Fe$_2$As$_2$. In the effective field model given by Eq. \cite{1}, the relation between $g$ and $w$ determines whether the nematic order is present or not. As pointed out previously in Refs. \cite{10,18,65}, when $g > \max(0, −w)$, only one of the two order parameters $M_X$ and $M_Y$ develops a finite mean value due to tetragonal symmetry breaking, which is a clear signature for the existence of a nematic order. On the other hand, we have $\langle M_X \rangle = \langle M_Y \rangle$ if $g < \max(0, −w)$, which implies the absence of nematic order \cite{10,18,65}. This property will be used to judge whether the nematic critical line bends back.

To examine how the relation between $g$ and $w$ varies with decreasing $T$, we have solved the RG equations and obtained its dependence on the running length scale $l$. To be specific, we have chosen the following bare values of model parameters: $a_s^0 = −0.001$, $w_0 = 0.05$, $w_0 = 0.01$, $g_0 = 0.01$, $\lambda^0 = 0.01$, $\lambda_{\Delta A}^x = 1.0 \times 10^{-8}$. We consider several representative values of $w_0$: $w_0 = 0.1u_0$, $0.3u_0$, $0.5u_0$, and $1.2u_0$. The $l$-dependence of these parameters can be easily converted to a $T$-dependence by utilizing

![Graph](image-url)
the transformation $T = T_0 e^{-l}$, where $T_0$ is some reference temperature smaller than $T_c$. The numerical results are presented in Fig. 2(a). We now determine whether the nematic state becomes a non-nematic state as $T$ is lowered down to zero on the basis of these results.

There are in principle two possibilities about the slopes of nematic transition line $T_{m4}$, as schematically shown in Fig. 3. We consider an arbitrary point $A$ lying slightly below the transition line $T_{m4}$. At point $A$, the system is in the nematic state with $g > \max(0, -w)$. We then lower $T$ along the route $A \to B$. If the inequality $g > \max(0, -w)$ is always satisfied as $T \to 0$ along $A \to B$, the system is always in the nematic state and the slope of the transition line $T_{m4}$ is negative. This corresponds to the case represented by Fig. 3(a). In contrast, if the condition $g > \max(0, -w)$ is violated as $T$ is reduced to certain value, the second possibility shown in Fig. 3(b) occurs.

In this case, the nematic state becomes non-nematic once again and the slope of transition line becomes positive at lower temperatures, exhibiting back-bending behavior. The numerical results of Eq. (8) informs that the ratio $g/w$ is large for various values of $l$, wherein $w$ may be both positive and negative (it is negative for the curve shown in Fig. 1). From the asymptotic behaviors of $g(l)$ presented in Fig. 2(a) and $g(l)/w(l)$ presented in Fig. 4 we infer that the inequality $g > \max(0, -w)$ remains true as $T \to 0$ if it is satisfied at the starting point $A$. This clearly indicates that the nematic transition line $T_{m4}$ has a negative slope inside the SC dome and never bends backwards, which is well consistent with the observed phase diagram 26.

B. Suppression of superconductivity due to ordering competition

We now verify whether superconductivity is suppressed by ordering competition in the vicinity of the magnetic QCP. To this end, we will compute the superfluid density of superconductor has the generic form $\rho_s(T) = \rho^A_s(T) - \rho_n(T)$, where $\rho^A_s(T)$ can be evaluated by virtue of the formula $\rho^A_s(T) \propto \alpha_A(T)$ with $\alpha_A(T)$ being the mass for vector potential $A$ generated via Anderson-Higgs mechanism 15 and $\rho_n(T)$ is the density of thermally excited normal (non-SC) fermionic quasiparticles.

In this work, we consider only the competition between distinct order parameters and neglect the contribution of the normal component, i.e. $\rho_n(T) \ll \rho^A_s(T)$, which is possible for the $T \ll T_c$, focusing on how superfluid density is modified by ordering competition. To determine the impact of ordering competition, we suppose a specific temperature $T_0$ as a reference, and then examine how superfluid density $\rho_s$ varies as a function of the ratio $T/T_0$. We assume that $T_0$ is well below $T_c$ so that the normal fermionic quasiparticles can nearly be neglected and hence $\rho_s(T) \sim \rho^A_s(T)$. From the results displayed in Fig. 2(b), we can see that $\rho^A_s(T)$ is strongly dependent of $T$ in the presence of ordering competition and decreases rapidly as $T/T_0$ grows. It is thus clear that the superfluid density is strongly suppressed by ordering competition and approximately goes to zero in the vicinity of the point $C$, where $T \approx 0.8 T_0$.

We then consider the impact of ordering competition on $T_c$. The value of $T_c$ can be determined by solving the equation $\rho_s(T_c) = \rho^A_s(T_c) - \rho_n(T_c) = 0$. Although the contribution $\rho_n(T_c)$ is not known, we can still infer that $T_c$ is suppressed by ordering competition because $\rho_s$ is significantly reduced. As shown in Fig. 2(b), $\rho_s(T)$ vanishes at certain point with $T < T_0$ ($T \approx 0.8 T_0$). This conclusion is well consistent with recent experiment 26, in which a considerable drop of $T_c$ is observed near the putative magnetic QCP. In an improved theoretic treatment, one would compute $\rho_n(T)$ by incorporating the contribution.
of fermionic quasiparticles. Notice that these quasiparticles are not free, but couple strongly to the SDW order parameter at the magnetic QCP. Usually, this coupling tends to excite more fermionic quasiparticles out of the SC condensate, which further suppresses the superfluid density and reduces $T_c$.

C. $C_4$ symmetric magnetic order

We finally turn to analyze the property of $C_4$ symmetric magnetic state. To uncover the effects caused by ordering competition, we consider the evolution of the system along the route $D \rightarrow E \rightarrow F$, shown in Fig. 1 and examine how $g$ and $w$ vary along this route.

Eq. (4) clearly shows that $w$ is associated with the quadratic term of $C_4$ SDW order parameter. In analogy to the nematic transition, the sign of $w$ determines which sort of $C_4$ SDW order, either SVC or CSDW, is realized. In particular, a $C_4$ SVC order is generated for $g < 0$ and $w > 0$, whereas $g < -w$ and $w < 0$ implies the occurrence of a $C_4$ CSDW order. By paralleling the analysis made for nematic critical line, we convert the $l$-dependence of $w$ using the transformation $T = T_0 e^{-l}$. If one assumes that $w$ is negative at the starting point $D$, which amounts to supposing the system is in the CSDW-type $C_4$ magnetic state, it remains negative as $T$ decreases down to the $F$ point, as can be clearly seen from Fig. 5(b). This result implies that CSDW state is stable in the low-$T$ region. On the other hand, if one starts from a positive $w$, corresponding to a SVC-type $C_4$ magnetic state, we show in Fig. 5(b) that $w$ eventually becomes negative at some critical $T$, which can be identified as the $E$ point. It follows that the SVC state is unstable in the low-$T$ region, and that the CSDW state is more favorable.

We conclude from the above analysis that, although in principle either SVC or CSDW type $C_4$ state could be realized in the high-$T$ region, the CSDW-type $C_4$ state is the only stable one in the low-$T$ region. In a recent work, Christensen et al. have suggested the spin-orbit coupling gives rises to the CSDW-type $C_4$ SDW. Additionally, Hoyer et al. have studied the disorder effects and demonstrated that impurity scattering favors CSDW over SVC. Here, we provide a different approach to determine the nature of $C_4$ symmetric magnetic order. Moreover, the sudden drop of $w$ at certain critical energy scale usually indicates the happening of a first-order transition, which is qualitatively consistent with recent experiments.

IV. COMPARISON TO Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$

We now compare the present RG results with a previous work, which investigated the impact of ordering competition on the global phase diagram of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$. Both Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and Ba$_{1-x}$K$_x$Fe$_2$As$_2$ belong to the 122 family of FeSCs, and display a complicated phase diagram. A common feature is that, over a large part of their phase diagrams, superconductivity coexists and competes with a SDW type magnetic order and a nematic order. The ordering competition and its effects on the phase diagram can be described by deriving an effective low-energy field theory which is supposed to contain several distinct order parameters. Such an effective theory is expected to be as general as possible, and applicable in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, Ba$_{1-x}$K$_x$Fe$_2$As$_2$, and other similar 122 FeSCs.

However, there are some important differences between the compounds Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and Ba$_{1-x}$K$_x$Fe$_2$As$_2$. In Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, there is only a $C_2$ symmetric stripe-type SDW order. In contrast, there are both $C_2$ and $C_4$ symmetric magnetic states in Ba$_{1-x}$K$_x$Fe$_2$As$_2$. 

and a number of other hole-doped 122 FeSCs \cite{21,28}. Moreover, the nematic transition line exhibits completely different doping dependence in the SC dome of these two FeSCs: it has a positive slope inside the SC dome of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ \cite{64}, but a negative slope inside the SC dome of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ \cite{26}.

To capture both the similarity and difference, the model of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ should be formally analogous but not identical to that of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ \cite{65}. It was suggested in Refs.\cite{33,34} that the C4 symmetric magnetic order that emerges in Ba$_{1-x}$K$_x$Fe$_2$As$_2$ can be described by introducing a new term $-(M_X \times M_Y)^2$. As shown previously in Ref.\cite{65}, in the absence of this term, ordering competition gives rise to the suppression of superconductivity and in particular the positive slope of nematic transition line in the SC dome, which are in good agreement with experiments performed in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ \cite{64}. In the current work, we have demonstrated through RG calculations that, adding the above new term leads to the suppression of superconductivity near the magnetic QCP and also the negative slope of nematic transition line in the SC dome of Ba$_{1-x}$K$_x$Fe$_2$As$_2$, which is qualitatively consistent with recent experiments \cite{25,28}. Furthermore, our RG analysis revealed that the CSDW-type C4 magnetic state is more favorable than the SVC-type C4 magnetic state, and hence can be used to determine the nature of C4 magnetic state observed in Ba$_{1-x}$K$_x$Fe$_2$As$_2$ \cite{26}. It is therefore clear that the effective model of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ can be properly modified to describe Ba$_{1-x}$K$_x$Fe$_2$As$_2$, and that the same perturbative RG scheme used in Ref.\cite{65} and here can be applied to account for both the similarity and difference between Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and Ba$_{1-x}$K$_x$Fe$_2$As$_2$.

V. SUMMARY AND DISCUSSION

In summary, we have studied the impact of the competition between superconductivity and C2 and C4 symmetric magnetic orders in a hole-doped FeSC Ba$_{1-x}$K$_x$Fe$_2$As$_2$. After performing a detailed RG analysis within an effective field theory, we have reproduced a number of interesting features of the global phase diagram. In particular, our RG analysis have showed that the order parameter fluctuation and ordering competition lead to moderate suppression of superconductivity near the magnetic QCP, maintain the negative slope of nematic critical line in the SC dome, and also sort out the CSDW-type C4 magnetic order as the more stable state than a SVC-type C4 magnetic order in the low-$T$ regime. All these theoretic results are well consistent with the recent experiments of Ref. \cite{26}, and schematically summarized in Fig. \ref{fig:global_phase_diagram}.

Our RG calculations are confined to the small region surrounding the magnetic QCP in the SC dome. To gain a better knowledge of the entire phase diagram, it is necessary to consider the non-SC phase above $T_c$. A salient feature observed in Ref. \cite{26} is the back-bending behavior of a critical line between nematic (C2 SDW) to pure C4 SDW orders, namely $T_{M4}$, which turns out to be induced by the emergence of C4 symmetric magnetic order. The transition line $T_{M4}$ exists well above $T_c$, thus there is no SC order and the competition between SC and magnetic order parameters is unlikely to be important. It turns out that the underlying mechanism for the back-bending behavior of $T_{M4}$ is entirely different from that is used to account for the slope of $T_m$ in the SC dome. We believe that an essential role is played by elementary fermionic degrees of freedom, which are strongly suppressed below $T_c$ by the SC gap but should be present above $T_c$. The inter-fermion interaction is expected to be responsible for the transition between C4 and C2 symmetric magnetic states. This problem is made more complicated by the uncertainty of the nature of C4 symmetric magnetic order. In the SC dome below $T_c$, ordering competition lifts the degeneracy between CSDW and SVC states at low energies, and chooses CSDW as the true ground state. However, order competition is much less important above $T_c$. It remains unclear whether the CSDW or SVC state is realized in the region between $T_{M4}$ and $T_c$. The microscopic mechanism for the back-bending behavior of $T_{M4}$ could be properly understood only after the nature of C4 symmetric magnetic order is identified, which is subject to future research.

In this paper, we have considered only one specific compound Ba$_{1-x}$K$_x$Fe$_2$As$_2$. Recent experiments of Hardy et al. \cite{26} provided a clear and detailed global phase diagram of Ba$_{1-x}$K$_x$Fe$_2$As$_2$, which gives us a good opportunity to directly compare our RG results with experimental results. Apart from Ba$_{1-x}$K$_x$Fe$_2$As$_2$, the C4 symmetric magnetic order also exists in a number of other hole-doped FeSCs, including Ba(Fe$_{1-x}$Mn$_x$)$_2$As$_2$ \cite{21}, Ba$_{1-x}$Na$_x$Fe$_2$As$_2$ \cite{22,23}, and Sr$_{1-x}$K$_x$Fe$_2$As$_2$ \cite{24}. It should be possible to generalize our RG approach to study the global phase diagrams of these three FeSCs. However, there might be important difference between Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and these FeSCs. In that case, the effective field-theoretic model given by Eq. \ref{effective_action} needs to be properly modified. Once the modified effective model is specified, it is straightforward to carry out RG calculations, just as what we have done in this work.

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