

Hole density dependent magnetic structure and anisotropy in Fe-pnictide superconductor

Yuan-Fang Yue(岳远放), Zhong-Bing Huang(黄忠兵), Huan Li(黎欢), Xing Ming(明星), and Xiao-Jun Zheng(郑晓军)

Citation: Chin. Phys. B, 2023, 32 (**9**): 097403. DOI: 10.1088/1674-1056/acd328
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Raman phonon anomalies in $Sr(Fe_{1-x}Co_x)_2As_2$

Yanxing Yang(杨彦兴), Hewei Zhang(张鹤巍), and Haizheng Zhuang(庄海正)
Chin. Phys. B, 2022, 31 (**2**): 027401. DOI: 10.1088/1674-1056/ac0cd6

A single-crystal neutron diffraction study on magnetic structure of $CsCo_2Se_2$

Juanjuan Liu(刘娟娟), Jieming Sheng(盛洁明), Wei Luo(罗伟), Jinchen Wang(汪晋辰), Wei Bao(鲍威), Jinhu Yang(杨金虎), Minghu Fang(方明虎), S A Danilkin
Chin. Phys. B, 2018, 27 (**11**): 117401. DOI: 10.1088/1674-1056/27/11/117401

Interplay of iron and rare-earth magnetic order in rare-earth iron pnictide superconductors under magnetic field

Lei-Lei Yang(杨雷雷), Da-Yong Liu(刘大勇), Dong-Meng Chen(陈东猛), Liang-Jian Zou(邹良剑)
Chin. Phys. B, 2016, 25 (**2**): 027401. DOI: 10.1088/1674-1056/25/2/027401

First-principles study of FeSe epitaxial films on $SrTiO_3$

Liu Kai (刘凯), Gao Miao (高淼), Lu Zhong-Yi (卢仲毅), Xiang Tao (向涛)
Chin. Phys. B, 2015, 24 (**11**): 117402. DOI: 10.1088/1674-1056/24/11/117402

Variational Monte Carlo study of the nematic state in iron-pnictide superconductors with a five-orbital model

Zheng Xiao-Jun (郑晓军), Huang Zhong-Bing (黄忠兵), Zou Liang-Jian (邹良剑)
Chin. Phys. B, 2015, 24 (**1**): 017404. DOI: 10.1088/1674-1056/24/1/017404

Hole density dependent magnetic structure and anisotropy in Fe-pnictide superconductor

Yuan-Fang Yue(岳远放)[1,2], Zhong-Bing Huang(黄忠兵)[3,†], Huan Li(黎欢)[1,2], Xing Ming(明星)[1,2], and Xiao-Jun Zheng(郑晓军)[1,2,‡]

[1] *College of Science, Guilin University of Technology, Guilin* 541004, *China*
[2] *Key Laboratory of Low-dimensional Structural Physics and Application, Education Department of Guangxi Zhuang Autonomous Region, Guilin* 541004, *China*
[3] *Faculty of Physics, Hubei University, Wuhan* 430062, *China*

(Received 27 March 2023; revised manuscript received 26 April 2023; accepted manuscript online 6 May 2023)

The competition between different magnetic structures in hole-doped Fe-pnicitides is explored based on an extended five-orbital Hubbard model including long-range Coulomb interactions. Our results show that the stabilized magnetic structure evolves with increasing hole doping level. Namely, the stripe antiferromagnetic phase dominates at zero doping, while magnetic structures with more antiferromagnetic linking numbers such as the staggered tetramer, staggered trimer, and staggered dimer phases become energetically favorable as the hole density increases. At a certain doping level, energy degeneracy of different magnetic structures appears, indicating strong magnetic frustration and magnetic fluctuations in the system. We suggest that the magnetic competition induced by the hole doping may explain the fast decrease of the Neel temperature T_N and the moderately suppressed magnetic moment in the hole doped Fe-pnicitides. Moreover, our results show a sign reversal of the kinetic energy anisotropy as the magnetic ground state evolves, which may be the mechanism behind the puzzling sign reversal of the in-plane resistivity anisotropy in hole-doped Fe-pnicitides.

Keywords: iron-pnictide superconductors, magnetic structure, resistivity anisotropy

PACS: 74.25.Jb, 74.70.Xa, 71.10.Fd **DOI:** 10.1088/1674-1056/acd328

1. Introduction

The phase diagram of Fe-pnictides is very similar to the one in copper oxides, in the sense that the high temperature superconductivity emerges in both materials when an antiferromagnetic (AFM) state is suppressed by carrier doping. For this reason, understanding the nature of the magnetism and its doping dependence in these materials is believed to be key in explaining their high-T_c superconductivity.[1–6]

The nature of the magnetism in Fe-pnictides is, however, quite different from the one in cuprates. Firstly, unlike the (π,π) ordered antiferromagnets in the undoped cuprates, the parent phase in Fe-pnicitides is a stripe-like antiferromagnetic (str-AFM) state with a wave-vector $\boldsymbol{Q}_1 = (\pi,0)$ or $\boldsymbol{Q}_2 = (0,\pi)$.[7,8] This str-AFM state breaks the tetragonal C_4 point-group symmetry of the system down to the orthorhombic C_2 symmetry, and it is accompanied by a tetragonal-to-orthorhombic structural distortion and in-plane anisotropies in several observables, such as an orbital ordered polarization of d_{xz} and d_{yz} of Fe,[9,10] anisotropies in the optical spectrum,[11,12] as well as anisotropic dc conductivities.[13] Secondly, unlike the strong correlated antiferromagnetic Mott insulator phase with an electron occupation $n = 1$ (half-filling) in the parent cuprates, the parent antiferromagnetic phase of Fe-pnicitdes is a weak/moderate correlated bad metal with an electron filling $n = 6$ per Fe (with an average orbital occupation $n_{\rm obt} = n/5 = 1.2$).[7,8]

Various techniques demonstrate that in hole doped Fe-pnictide, the effective mass of carriers is enhanced as the filling is reduced, namely, electronic correlations increase monotonically with hole doping.[14–29] This behavior is understandable as $n_{\rm obt}$ approaches half filling by hole doping. However, contrary to the significant enhancement of the correlations, it is intriguing to note that the magnetism is rapidly suppressed as the hole-carriers are doped into the system. Moreover, Muon spin rotation and infrared spectroscopy study showed that the Fe magnetic moment is only moderately suppressed in most of the underdoped region where it decreases more slowly than the Neel temperature T_N.[30] This result indicates the complexity of the magnetism in the hole-doped Fe-pnicitdes, and a further investigation is needed to reveal why the electronic correlation and magnetism behave in the opposite way.

Besides the magnetism, the evolution of the in-plane resistivity anisotropy with hole doping is also intriguing and unusual. Recently, it was observed that the anisotropy resistivity changes sign from $\rho_b - \rho_a > 0$ to $\rho_b - \rho_a < 0$ across the doping phase diagram of Fe-pnictides.[31,32] This behavior has been widely discussed while the mechanism behind it is still controversial.[33–36] More intriguingly, a temperature-dependent sign reversal was observed in hole-doped $Ca_{1-x}Na_xFe_2As_2$.[32] That is, the anisotropic transport

†Corresponding author. E-mail: huangzb@hubu.edu.cn
‡Corresponding author. E-mail: xjzheng@glut.edu.cn

© 2023 Chinese Physical Society and IOP Publishing Ltd

evolves from $\rho_b - \rho_a > 0$ at high temperature, but still under T_N, to $\rho_b - \rho_a < 0$ at low temperature. This behavior can not be explained by the spin fluctuation[33–35] and the ellipticity of the FSs[31,36] since under the magnetically ordered state the FSs are strongly renormalized. Instead, it indicates that there may be a competition between different orders at this level of hole doping, and it is likely that their contributions to the resistivity anisotropy are diverse and temperature dependent.[32]

In this study, we perform a comprehensive investigation on the hole-doping dependent magnetism of Fe-pnictides based on a five-orbital extended Hubbard model.[37–39] The primary result of our study is that the magnetic structures of Fe-pnictides evolve with hole doping. The stabilities of the magnetic structures are demonstrated to be very sensitive to the hole-doping levels, as a result, fierce magnetic competition/frustration emerges at certain hole concentrations. Namely, when the str-AFM structure is dominant in the parent phase, magnetic structures with an increasing number of nearest-neighbors antiferromagnetic links, such as the staggered tetramer antiferromagnetic (tet-AFM) state with $\boldsymbol{Q}_{\rm tet} = (\pi, \pi/4)$, staggered trimer antiferromagnetic (tri-AFM) state with $\boldsymbol{Q}_{\rm tri} = (\pi, \pi/3)$ and staggered dimer antiferromagnetic (dim-AFM) state with $\boldsymbol{Q}_{\rm dim} = (\pi, \pi/2)$, become energetically more favorable as hole doping increases.

We argue that this hole-doping induced magnetic competition and magnetic frustration may contribute to the suppression of long-range magnetic ordering, which has been discussed in the case of FeSe,[40] and it may explain the fast decrease of the Neel temperature T_N and the moderately suppressed magnetic moment in the hole-doped Fe-pnicitide. What's more, we find that the signs of the kinetic energy anisotropies are different for different magnetic structures, as a result, the kinetic energy anisotropy of the system changes sign as the magnetic structures evolve with doping, which we believe is responsible for the sign reversal of the resistivity anisotropy that observed experimentally.

Our paper is organized as follows: In Section 2, we define the Hamiltonian and describe the calculation methods. In Section 3, we present our numerical results and discuss their relation to the experimental measurements. Finally, we make some concluding remarks in Section 4.

2. Model

The tight-binding model we use is the one derived by Kuroki *et al.*[41] As one of the most intensively studied models for Fe-pnictides, it has explained or well reproduced a variety of experimental phenomena, not only for LaFeAsO but also for other classes of Fe-pnictides. Therefore, in this paper we focus on this tight-binding model, irrespective of other Fe-pnictides models which may have some difference in the electronic structures but do not affect the basic physical properties.[42] The electronic correlations we consider here include the intraorbital and interorbital Coulomb interactions U_1 and U_2, the Hund's coupling J, and the off-site Coulomb interaction V between nearest-neighbor (NN) sites:

$$\begin{aligned} H =& H_{\rm TB} + U_1 \sum_{i\alpha} n_{i\alpha\uparrow} n_{i\alpha\downarrow} \\ &+ \sum_{i,\alpha<\beta,\sigma,\sigma'} [(U_2 - J\delta_{\sigma\sigma'}) n_{i\alpha\sigma} n_{i\beta\sigma'}] \\ &+ J \sum_{i,\alpha<\beta} (c^\dagger_{i\alpha\uparrow} c^\dagger_{i\beta\downarrow} c_{i\alpha\downarrow} c_{i\beta\uparrow} + c^\dagger_{i\alpha\uparrow} c^\dagger_{i\alpha\downarrow} c_{i\beta\downarrow} c_{i\beta\uparrow} + \text{H.c.}) \\ &+ V \sum_{\langle ij \rangle} n_i n_j. \end{aligned} \tag{1}$$

The reason we include V into the Hamiltonian is that V has been proved to have an important effect on the properties of iron-based superconductors, especially on the nematicity and magnetism. In the following we show that the introduction of V improves the magnetism's sensitivity to hole doping. For simplicity, in our calculations we propose that V is orbital independent, and its value is set to be 0.5–0.75 eV according to the *ab initio* calculation.[43] What's more, to eliminate the double counting of V, we subtract the purely electrostatic term, which corresponds to the first term of the following expression:

$$\begin{aligned} V \sum_{\langle ij \rangle} n_i n_j =& V \sum_{\langle ij \rangle} \langle n_i \rangle n_j - V \sum_{\langle ij \rangle \sigma\sigma'} \langle C^\dagger_{i\sigma} C_{j\sigma'} \rangle C^\dagger_{j\sigma'} C_{i\sigma} \\ &- V \sum_{\langle ij \rangle} \langle n_i \rangle \langle n_j \rangle + V \sum_{\langle ij \rangle \sigma\sigma'} |\langle C^\dagger_{i\sigma} C_{j\sigma'} \rangle|^2. \end{aligned} \tag{2}$$

One can see that the first term in Eq. (2) depends on the average density on the sites, thus it is reasonable to assume that this term is already captured by the DFT.[44] Thus, in our following calculations we subtract it to eliminate the double counting. The second term is the exchange term which modifies the hopping amplitudes and leads to the renormalization of the band structure.[39,45]

In our calculations, the expectation value of the interaction Hamiltonian is evaluated by Wick's theorem, and the two-operator contractions of the form $\langle \varphi_1 \varphi_2 \rangle$ (where φ refers to c_i or $c_i^\dagger$) will only be considered when they keep the symmetries of the original Hamiltonian.

The mean-field wave functions $|\psi_{\rm MF}\rangle$ for the magnetic phase are the ground states of the following mean field Hamiltonian:

$$H_{\rm M} = H_{\rm TB} + \sum_{i\alpha\sigma} \sigma [\Delta_{\rm M}(\alpha) e^{i \boldsymbol{R}_i \cdot \boldsymbol{Q}}] n_{i\alpha\sigma}. \tag{3}$$

Here $\Delta_{\rm M}$ denotes the magnetic ordering parameters. The magnetic wave vectors are set to be $\boldsymbol{Q}_{\rm str} = (\pi, 0)$, $\boldsymbol{Q}_{\rm tet} = (\pi, \pi/4)$, $\boldsymbol{Q}_{\rm tri} = (\pi, \pi/3)$, and $\boldsymbol{Q}_{\rm dim} = (\pi, \pi/2)$, corresponding to str-AFM structure, tet-AFM structure, tri-AFM structure and dim-AFM structure, respectively. All these four magnetic structures are illustrated in Fig. 1.

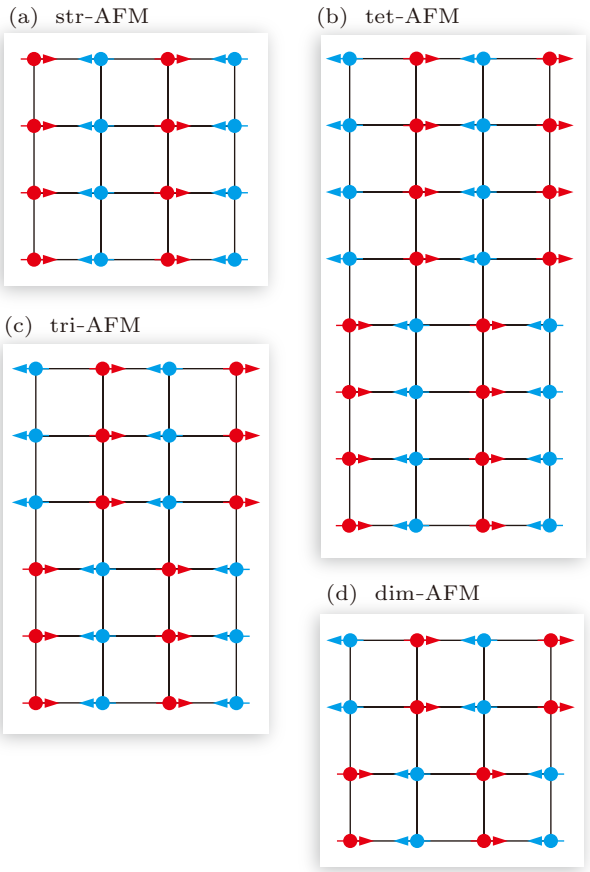


Fig. 1. Pattern definitions for the magnetic structures: (a) str-AFM, (b) tet-AFM, (c) tri-AFM, (d) dim-AFM.

3. Results and discussion

Considering that the interaction strength in Fe-pnictides is moderate and material dependent, in our calculation we set $U_1 = 2.0$–3.0 eV, and $J/U_1 = 0.15$, 0.20, 0.25, with a well-known relation $U_2 = U_1 - 2J$. The magnitude of V is set to $V/U_1 = 0.25$, which is reasonable according to the *ab initio* calculations. In Fig. 2 we present the magnetic phase diagram as a function of dopant concentrations and interaction strengths. We can see that the magnetic structure of the system evolves from str-AFM to dim-AFM as occupation number changes from $n = 6.1$ to $n = 5.5$. Around $n = 6.0$, the str-AFM state dominates, which is in agreement with experiments for underdoped Fe-pnicitdes. As n decreases, the str-AFM is substituted by a tet-AFM state or a tri-AFM state. For $J = 0.15U_1$ [Fig. 3(a)], the str-AFM to tri-AFM phase transition emerges already around $n = 6.0$ for $U_1 \leq 2.2$. For $U_1 \geq 2.2$, a str-AFM to tet-AFM transition emerges as n decreases to 5.8, followed by a tet-AFM to tri-AFM transition around $n = 5.71$ and a tri-AFM to dim-AFM transition around $n = 5.61$. When J/U_1 increases to 2.0 [Fig. 3(b)] or 2.5 [Fig. 3(c)], the region of str-AFM dominants expands, and the critical occupation number, $n_{\rm crt}$, around which the phase transitions emerge slightly decreases. From Figs. 2(a)–2(c) we can see that the stabilities of the magnetic states are sensitively dependent on the occupation number. As the hole doping increases, the magnetic state with an increasing number of nearest-neighbors antiferromagnetic links, such as tet-AFM, tri-AFM and dim-AFM phases, becomes successively the energetically favorable state. Details may depend on the variations of the correlation strength, but the general trends are robust.

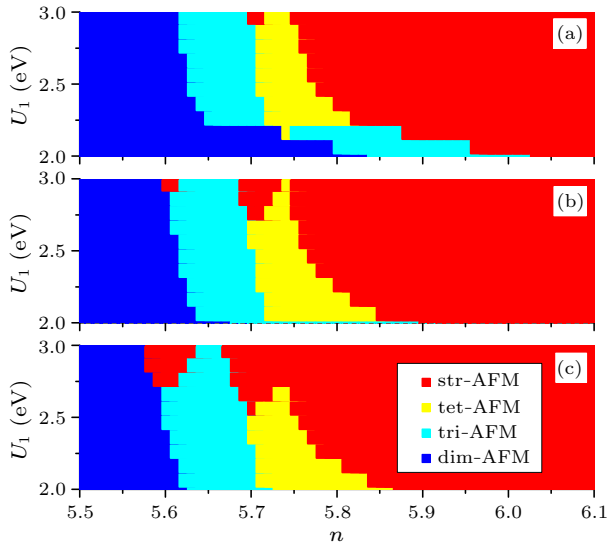


Fig. 2. Mean-field magnetic phase diagram as a function of U_1 and n. The relation $U_2 = U_1 - 2J$ is kept, $J/U_1 = 0.15$, 0.20, and 0.25 for (a), (b), and (c).

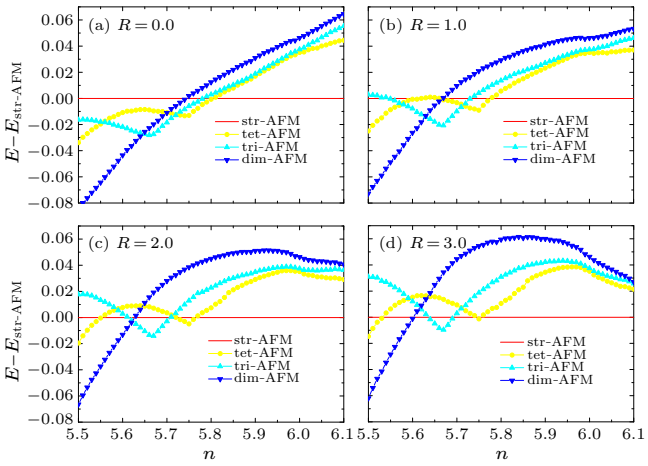


Fig. 3. Energies of the magnetic states refer to the energy of the str-AFM state as a function of n for (a) $R = 0.0$, (b) $R = 1.0$, (c) $R = 2.0$, (d) $R = 3.0$.

As mentioned above, the electron correlation strength increases with hole doping. With this in mind, we perform calculations in which the correlation strength increases linearly as hole doping increases. Specifically, we set

$$U_1^n = U_1^{n=6.0} + (6.0 - n)R, \tag{4}$$

with $U_1^{n=6.0} = 2.4$ eV.

Here R is the scaling factor which determines the increasing rate of the correlation strength as hole doping increases. For example, by choosing $R = 1.5$, we have U_1 increasing from 2.2 eV to 3.4 eV as n decreases from 6.1 to 5.5. J increases

from 0.33 eV to 0.51 eV, U_2 increases from 1.54 eV to 2.38 eV, V increases from 0.55 eV to 0.85 eV, by setting $J = 0.15U_1$, $U_2 = U_1 - 2J$, and $V/U_1 = 0.25$.

In Fig. 3, we present the energy differences between the str-AFM state and the other magnetic states as a function of n for $R = 0$, 1.0, 1.5, and 2.0. We can see that when the energy differences increase with R, the general trend is robust. Namely, as n decreases, the tet-AFM, tri-AFM and dim-AFM states become more energetic favorable successively. The first energy degeneration emerges at around $5.75 \leq n \leq 5.80$, depending on the value of R. These results indicate a hole-doping introduced magnetic frustration, and we suggest that it may contribute to the experimentally observed dropping of T_N.

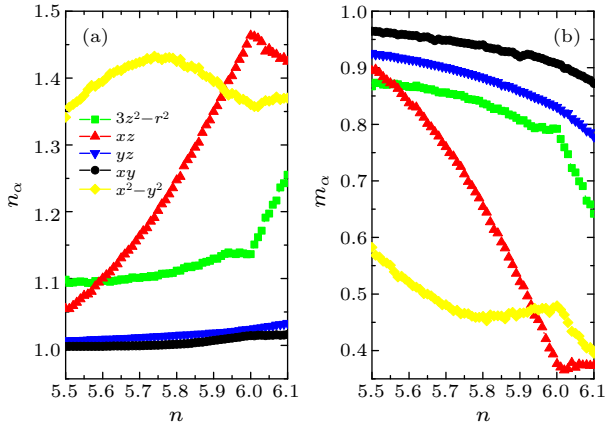


Fig. 4. (a) Orbital occupation number n_α and (b) orbital magnetic moment m_α in the str-AFM state as a function of the site occupation number n.

In Fig. 4, we present the orbital occupation number n_α and orbital magnetic moment m_α in the str-AFM state as a function of the site occupation number n. One can see that when n_{xz} decrease sharply with decreasing n compared to other orbital occupation numbers, m_{xz} increases fast with decreasing n. We note that $t_{xz,xz}[0,a_y]$ is much larger than $t_{xz,xz}[a_x,0]$ in our model, namely, the NN exchange coupling between the spins on the xz orbitals is anisotropic with the y-direction dominant the x-direction. Thus, as the orbital moment n_{xz} increases with hold doping as shown in Fig. 4(b), the total NN exchange coupling along the y-direction will enhance. As a result, the magnetic structures with an increasing number of NN antiferromagnetic links along the y-direction become energetically more favorable as hole doping increases. Our results demonstrate that orbital differentiation is crucial to address the magnetic softness and doping properties of Fe-pnictides.

In Fig. 5 we present the energies and the anisotropy of the kinetic energies of the magnetic states for $5.65 \leq n \leq 6.10$. The anisotropy of the kinetic energy along the x/y direction is defined as $\mathrm{kin}_{x/y} = \langle \sum_{i\alpha\beta\sigma,\Delta y=0/\Delta x=0} t_{\alpha\beta}[\Delta x,\Delta y] c^\dagger_{i,\alpha\sigma} c_{i+\Delta x/\Delta y,\beta\sigma} \rangle$. We can see that when the anisotropy in the str-AFM state remains large and positive in the hole-doped case, the anisotropies in the tet-AFM and tri-AFM states diminish and their sign change as hole doping increases. This result suggests that as the magnetic state evolves from str-AFM to tet-AFM or tri-AFM, as illustrated in Fig. 5(a), the sign of the anisotropy of the kinetic energy also changes. As shown in the earlier work,[37] kinetic energy is closely related to Drude weight, and anisotropic kinetic energy will result in anisotropic dc conductivities. We believe that this sign reversal of the kinetic energy obtained here may be manifested as the sign reversal of the resistivity observed in the hole-doped Fe-pnictides.[31,32] What's more, it can explain the temperature dependent sign reversal in hole-doped $Ca_{1-x}K_xFe_2As_2$.[32] For $n < 5.77$, the anisotropy is small and negative at low temperature since the tet-AFM or tri-AFM state is dominant. At higher temperature, the str-AFM fluctuation may arise since the energy of str-AFM state is slightly higher than the ground state, and then the large positive anisotropy caused by the srt-AFM fluctuation may change the sign of the anisotropy in the system from negative to positive. Namely, sensitive doping dependent magnetic competition is behind the sensitive doping dependent anisotropy observed in the hole-doping Fe-pnicites.

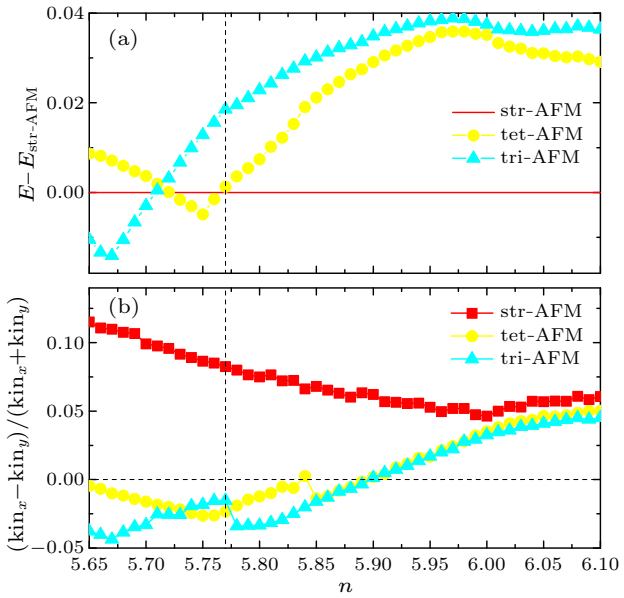


Fig. 5. (a) Energies of the magnetic states refer to the energy of the str-AFM state as a function of n. (b) Anisotropy of the kinetic energies obtained in the magnetic states as a function of n. The vertical dashed lines indicate the doping point at which the str-AFM state and tet-AFM state are degenerate.

4. Conclusions

In summary, we have carried out a comprehensive investigation based on a realistic extended five-orbital model. Our results demonstrate that the stability of magnetic structure is very sensitive to the hole-doping levels and magnetic frustrations arise due to the fierce competition between magnetic structures at certain levels of hole doping. We consider that these frustrations contribute to the experimentally

observed dropping of T_N with hole doping, explaining the intriguing magnetic behavior which is contrary to the electronic correlation. What's more, our results show that the kinetic energy anisotropies change sign as the stabilized magnetic states change with doping, which may be responsible for the puzzling sign reversal of the resistivity anisotropy found in hole-doped $Ca_{1-x}K_xFe_2As_2$.

Acknowledgments

Project supported by the Guangxi Natural Science Foundation, China (Grant Nos. 2022GXNSFAA035560 and GuikeAD20159009) and the Scientific Research Foundation of Guilin University of Technology (Grant No. GLUTQD2017009).

References

[1] Lee P A, Nagaosa N and Wen X G 2006 *Rev. Mod. Phys.* **78** 17
[2] Fradkin E, Kivelson S A and Tranquada J M 2015 *Rev. Mod. Phys.* **87** 457
[3] Inosov D S 2016 *Comptes Rendus Phys.* **17** 60
[4] Bascones E, Valenzuela B and Calderon M J 2016 *Comptes Rendus Phys.* **17** 36
[5] Yang J, Zhou R, Wei L L, Yang H X, Li J Q, Zhao Z X and Zeng G Q 2015 *Chin. Phys. Lett.* **32** 107401
[6] Hong X C, Wang A F, Zhang Z, Pan J, He L P, Luo X G, Chen X H and Li S Y 2015 *Chin. Phys. Lett.* **32** 127403
[7] Johnston D C 2010 *Adv. Phys.* **59** 803
[8] Dai P C, Hu J P and Dagotto E 2012 *Nat. Phys.* **8** 709
[9] Yi M, Lu D, Chu J H, Analytis J G, Sorini A P, Kemper A F, Moritz B, Mo S K, Moore R G, Hashimoto M, Lee W S, Hussain Z, Devereaux T P, Fisher I R and Shen Z X 2011 *Proc. Natl. Acad. Sci. USA* **108** 6878
[10] Jiang Q, Kang Y T and Yao D X 2013 *Chin. Phys. B* **22** 087402
[11] Nakajima M, Liang T, Ishida S, Tomioka Y, Kihou K, Lee C H, Iyo A, Eisaki H, Kakeshita T, Ito T and Uchida S 2011 *Proc. Natl. Acad. Sci. USA* **108** 12238
[12] Dusza A, Lucarelli A, Pfuner F, Chu J H, Fisher I R and Degiorg L 2011 *Europhys. Lett.* **93** 37002
[13] Chu J H, Analytis J G, De Greve K, McMahon P L, Islam Z, Yamamoto Y and Fisher I R 2010 *Science* **329** 824
[14] de'Medici L, Giovannetti G and Capone M 2014 *Phys. Rev. Lett.* **112** 177001
[15] Hardy F, Burger P, Wolf T, Fisher R A, Schweiss P, Adelmann P, Heid R, Fromknecht R, Eder R, Ernst D, Lohneysen H and Meingast C 2010 *Europhys. Lett.* **91** 47008
[16] Popovich P, Boris A V, Dolgov O V, Golubov A A, Sun D L, Lin C T, Kremer R K and Keimer B 2010 *Phys. Rev. Lett.* **105** 027003
[17] Pramanik A K, Abdel-Hafiez M, Aswartham S, Wolter A U B, Wurmehl S, Kataev V and Büchner B 2011 *Phys. Rev. B* **84** 064525
[18] Mu G, Luo H, Wang Z, Shan L, Ren C and Wen H H 2009 *Phys. Rev. B* **79** 174501
[19] Kim J S, Kim E G, Stewart G R, Chen X H and Wang X F 2011 *Phys. Rev. B* **83** 172502
[20] Abdel-Hafiez M, Aswartham S, Wurmehl S, Grinenko V, Hess C, Drechsler S L, Johnston S, Wolter A U B, Büchner B, Rosner H and Boeri L 2012 *Phys. Rev. B* **85** 134533
[21] Degiorgi L 2011 *New J. Phys.* **13** 023011
[22] Li G, Hu W Z, Dong J, Li Z, Zheng P, Chen G F, Luo J L and Wang N L 2008 *Phys. Rev. Lett.* **101** 107004
[23] Yang J, Hüvonen D, Nagel U, Room T, Ni N, Canfield P C, Bud'ko S L, Carbotte J P and Timusk T 2009 *Phys. Rev. Lett.* **102** 187003
[24] Wang N L, Hu W Z, Chen Z G, Yuan R H, Li G, Chen G F and Xiang T 2012 *J. Phys.: Condens. Matter* **24** 294202
[25] Brouet V, Jensen M F, Nicolaou A, Taleb-Ibrahimi A, Le Fevre P, Bertran F, Forget A and Colson D 2012 arXiv:1105.5604 [cond-mat.supr-con]
[26] Yi M, Lu D H, Analytis J G, Chu J H, Mo S K, He R H, Moore R G, Zhou X J, Chen G F, Luo J L, Wang N L, Hussain Z, Singh D J, Fisher I R and Shen Z X 2009 *Phys. Rev. B* **80** 024515
[27] Ding H, Nakayama K, Richard P, Souma S, Sato T, Takahashi T, Neupane M, Xu Y M, Pan Z H, Fedorov A V, Wang Z, Dai X, Fang Z, Chen G F, Luo J L and Wang N L 2011 *J. Phys.: Condens. Matter* **23** 135701
[28] Yoshida T, Ideta S, Nishi I, Fujimori A, Yi M, Moore R G, Mo S K, Lu D H, Shen Z X, Hussain Z, Kihou K, Shirage P M, Kito H, Lee C H, Iyo A, Eisaki H and Harima H 2014 *Front. Phys.* 200017
[29] Terashima T, Kimata M, Kurita N, Satsukawa H, Harada A, Hazama K, Imai M, Sato A, Kihou K, Lee C H, Kito H, Eisaki H, Iyo A, Saito T, Fukazawa H, Kohori Y, Harima H and Uji S 2010 *J. Phys. Soc. Jpn.* **79** 053702
[30] Mallett B P P, Wang C N, Marsik P, Sheveleva E, Yazdi-Rizi M, Tallon J L, Adelmann P, Wolf T and Bernhard C 2017 *Phys. Rev. B* **95** 054512
[31] Blomberg E C, Tanatar M A, Fernandes R M, Mazin I I, Shen B, Wen H H, Johannes M D, Schmalian J and Prozorov R 2013 *Nat. Commun.* **4** 1914
[32] Ma J Q, Luo X G, Cheng P, Zhu N, Liu D Y, Chen F, Ying J J, Wang A F, Lu X F, Lei B and Chen X H 2014 *Phys. Rev. B* **89** 174512
[33] Liang S, Moreo A and Dagotto E 2013 *Phys. Rev. Lett.* **111** 47004
[34] Fernandes R M, Chubukov A and Schmalian J 2014 *Nat. Phys.* **10** 97
[35] Christensen M H, Kang J, Andersen B M and Fernandes R M 2016 *Phys. Rev. B* **93** 085136
[36] Fernandes R M, Abrahams E and Schmalian J 2011 *Phys. Rev. Lett.* **107** 217002
[37] Zheng X J, Huang Z B, Liu D Y and Zou L J 2015 *Phys. Rev. B* **92** 085109
[38] Zheng X J, Huang Z B and Zou L J 2015 *Chin. Phys. B* **24** 017404
[39] Jiang K, Hu J P, Ding H and Wang Z Q 2016 *Phys. Rev. B* **93** 115138
[40] Glasbrenner J K, Mazin I I, Jeschke H O, Hirschfeld P J, Fernandes R M and Valent R 2015 *Nat. Phys.* **11** 953
[41] Kuroki K, Onari S, Arita R, Usui H, Tanaka Y, Kontani H and Aoki H 2008 *Phys. Rev. Lett.* **101** 087004
[42] Brydon P M R, Daghofer M and Timm C 2011 *J. Phys.: Condens. Matter* **23** 246001
[43] Miyake T, Nakamura K, Arita R and Imada M 2010 *J. Phys. Soc. Jpn.* **79** 044705
[44] Belozerov A S, Korotin M A, Anisimov V I and Poteryaev A I 2012 *Phys. Rev. B* **85** 045109
[45] Zheng X J, Huang Z B, Li H, Yang F and Lin H Q 2019 *J. Phys.: Condens. Matter* **31** 055601