Magnetic and Ising quantum phase transitions in a model for isoelectronically tuned iron pnictides

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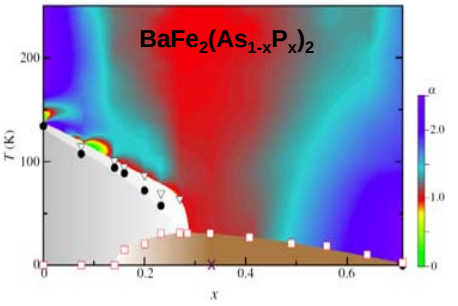
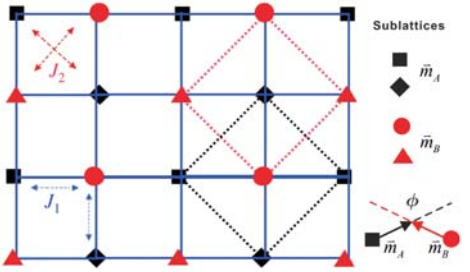


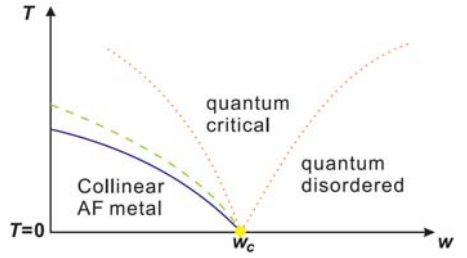
K. Hashimoto, et al., *Science* 336, 1554 (2012)
J. G. Analytis, et al., Nature Physics 10, 194 (2014)

Microscopic Picture



J_1–J_2 model on a square lattice. Two interpenetrating sub lattices with staggered magnetizations $\vec{m}_A$ and $\vec{m}_B$. The local moments are coupled to itinerant electrons

Schematic Phase Diagram Proposed for Isoelectronically Doped Iron Pnictides



It was suggested that the Ising and magnetic order phase transitions at *T*=0 are either two weakly separated 2nd order phase transition or concurrent as weakly 1st order phase transition. "w" is the spectral weight of coherent electrons

J. Dai, Q. Si, J-X Zhu, and E. Abrahams, PNAS, 106, 4118 (2009)
E.Abrahams and Q. Si, J. Phys.: Condens. Matter 23 223201 (2011)

The present work:

- **Study magnetic and Ising transitions at *T* = 0 in the presence of damping by conduction electrons.**
- **Study whether the two transitions are concurrent or separate at zero temperature.**

Quantum Landau-Ginzburg Theory

$$S = S_2 + S_4$$

$$S_2 = \sum_{\vec{q},i\omega_l}\left\{\chi_{0,\vec{q},i\omega_l}^{-1}\left(\left|\vec{m}_{A,\vec{q},i\omega_l}\right|^2+\left|\vec{m}_{B,\vec{q},i\omega_l}\right|^2\right)+2v(q_x^2-q_y^2)\vec{m}_{A,\vec{q},i\omega_l}\cdot\vec{m}_{B,-\vec{q},-i\omega_l}\right\}$$

$$S_4 = \int d\tau\int d\vec{r}\left\{u_1\left(\left|\vec{m}_A\right|^4+\left|\vec{m}_B\right|^4\right)+u_2\left|\vec{m}_A\right|^2\left|\vec{m}_B\right|^2-u_1\left(\vec{m}_A\cdot\vec{m}_B\right)^2\right\}$$

$$\chi_0^{-1}(\vec{q},i\omega_l) = r+\omega_l^2+cq^2+\gamma\left|\omega_l\right| \quad with \quad r=r_0+wA_Q$$

- **Early RG approach suggested that the transition could be weakly first order but is essentially continuous, implying quantum criticality.**
  J. Dai, Q. Si, J-X Zhu, and E. Abrahams, PNAS, 106, 4118 (2009)
  Y. Qi and C. Xu, Phys. Rev. B, 80, 094402 (2009)
- **We study the problem using a large-N approach.**

Free Energy to Leading Order in 1/N

$$f = \frac{\Delta_I^2}{u_I}-\frac{\left(m^2-r\right)^2}{2u_1+u_2}+(m^2\pm\Delta_I)\sigma^2$$
$$+\frac{1}{2}\frac{1}{\beta V}\sum_{\vec{q},i\omega_l}\ln\left[\left(\chi_{0,\vec{q},i\omega_l}^{-1}-r+m^2\right)^2-\left(v\left(q_x^2-q_y^2\right)+\Delta_I\right)^2\right]$$

$\Delta_I = \left\langle\vec{m}_A\cdot\vec{m}_B\right\rangle$ is Ising order parameter

σ is the collinear magnetic order parameter

$m^2 = \left\langle\vec{m}_A^2\right\rangle = \left\langle\vec{m}_B^2\right\rangle$ is mass term

J.Wu, Q.Si, and E. Abrahams, **arXiv:1406.5136**

Saddle-point Equations

$$0 = \left(\Delta_I\pm m^2\right)\sigma$$

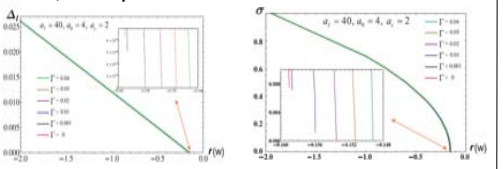
$$0 = \frac{\Delta_I}{u_I}+\sigma^2-\frac{1}{2\beta V}\sum_{\vec{q},i\omega_l}\frac{v\left(q_x^2-q_y^2\right)+\Delta_I}{\left(\chi_{0,\vec{q},i\omega_l}^{-1}-r+m^2\right)^2-\left(v\left(q_x^2-q_y^2\right)+\Delta_I\right)^2}$$

$$0 = -\frac{m^2}{2u_1+u_2}+\frac{r}{2u_1+u_2}+\sigma^2$$
$$+\frac{1}{2\beta V}\sum_{\vec{q},i\omega_l}\frac{\chi_{0,\vec{q},i\omega_l}^{-1}-r+m^2}{\left(\chi_{0,\vec{q},i\omega_l}^{-1}-r+m^2\right)^2-\left(v\left(q_x^2-q_y^2\right)+\Delta_I\right)^2}$$

- **Both magnetic and Ising order phase transitions at *T*=0 are very weakly first order.**
- **The two transitions at *T*=0 are concurrent.**

J.Wu, Q.Si, and E. Abrahams, **arXiv:1406.5136**

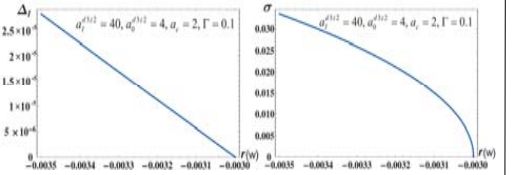
Ising and Magnetic Orders v.s. Tuning Parameter in d=2, z=2 systems



$$a_I^{d2z2} = \frac{c^{3/2}\Lambda_c}{u_I},\ a_0^{d2z2} = \frac{c^{3/2}\Lambda_c}{2u_1+u_2},\ a_c = \frac{c}{\sqrt{c^2-v^2}},\ \Gamma = \frac{\gamma}{c^{1/2}\Lambda_c}$$

- **Numerical results show that the two transitions are concurrent. The jumps are very small, and decrease as the damping rate increases. The results are consistent with RG analysis.**

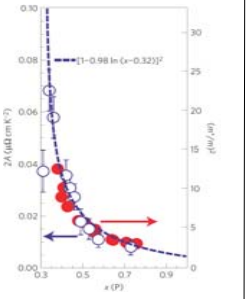
Ising and Magnetic Orders v.s. Tuning Parameter in d=3, z=2 systems



$$a_I^{d3z2} = \frac{c^{3/2}}{u_I},\ a_0^{d3z2} = \frac{c^{3/2}}{2u_1+u_2}$$

- **The two transitions are continuous when the spatial dimension is three. Again it is consistent with RG analysis.**

Our results provide an understanding of the quantum critical behavior observed in the field-induced normal state of P-doped $BaFe_2As_2$



J. G. Analytis, etc.,
Nature Physics 10, 194 (2014)

Summary

- **We studied zero-temperature magnetic and Ising transitions in a model for isoelectronically-tuned iron pnictides using a large-N approach.**
- **The two transitions are concurrent at *T* = 0. Both transitions are first-order, but the jumps of the orders are very small, and are suppressed by interlayer coupling.**
- **Quantum criticality occurs over a wide dynamical range, which is consistent with experimental observations.**