Загадочные спиральные магнетики MnSi и $Mn_{1-x}Fe_xSi$: скирмионы, магнитная фазовая диаграмма, квантовая критичность

С.В.Демишев

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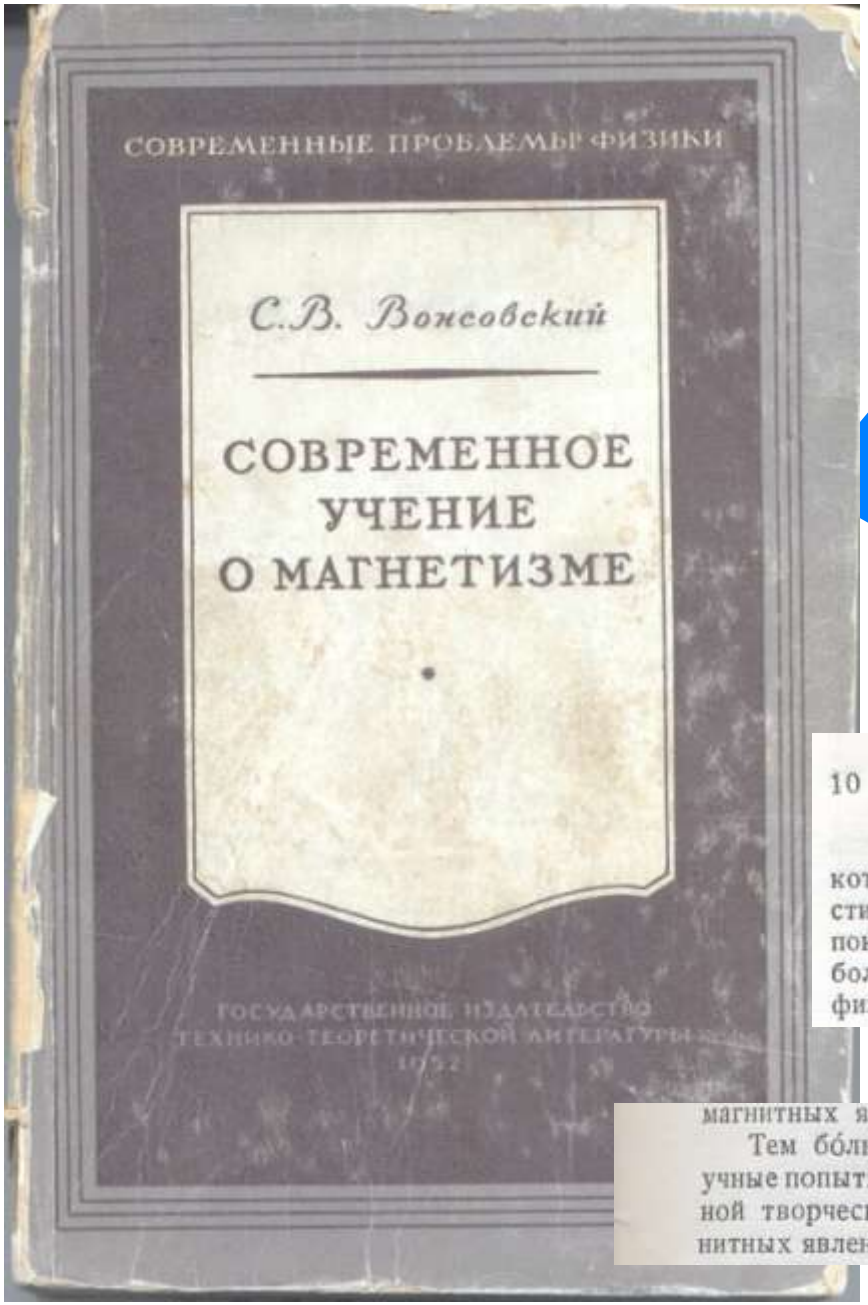
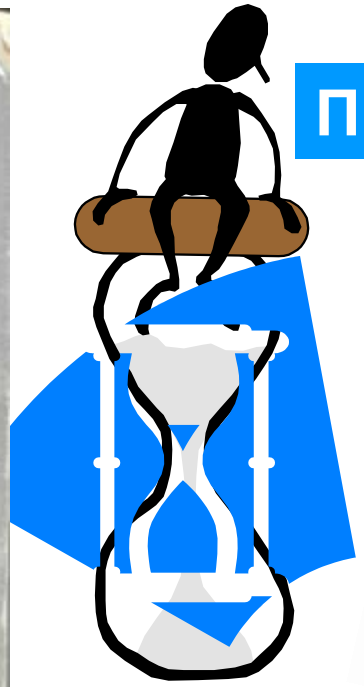
XIII Конференция молодых ученых
"Проблемы физики твердого тела и высоких давлений"
г. Сочи, пансионат «Буревестник», 12-21 сентября 2014 г.





ПРЕДИСЛОВИЕ

Нашим ученым присущ высокий советский патриотизм, который заставляет, в ответ на грубые выпады империалистической пропаганды в области науки, внести полную ясность, показав объективно, на конкретном материале самой науки большую и во многих областях ведущую роль советских физиков в развитии учения о магнетизме.

магнитных явлениях.

Тем бóльшим диссонансом звучат беспочвенные и антинаучные попытки умалить или игнорировать очевидный факт огромной творческой роли советской науки в области учения о магнитных явлениях со стороны ученых капиталистического мира [1]).

The metals MnSi, ($Mn_{1-x}Fe_xSi$) = itinerant magnets + spiral magnets

Itinerant magnet paradox:

$$\chi = \frac{C}{T - T_C};\ C \Rightarrow\ \mu^* \sim (1 \div 3)\mu_B\ \ (T > T_C)$$

$$T < T_C \Rightarrow\ \mu_{\text{sat}} \sim (0.1 - 0.5)\mu_B << \mu^*$$

Non-trivial physical situation!

Single ion with localized magnetic moment:

$$M = N\mu \cdot B_J(\mu \cdot B / k_B T)$$

$$\mu_{sat} = M(T \to 0)/N = \mu$$

$$J = 1/2 \qquad C = N\mu^2 / k_B$$

Spiral state is due to Dzyaloshinskii-Moriya interaction (DMI), which is allowed in the structures without inversion center.

PHYSICAL REVIEW B 73, 174402 (2006)

Cubic magnets with Dzyaloshinskii-Moriya interaction at low temperature

S. V. Maleyev*

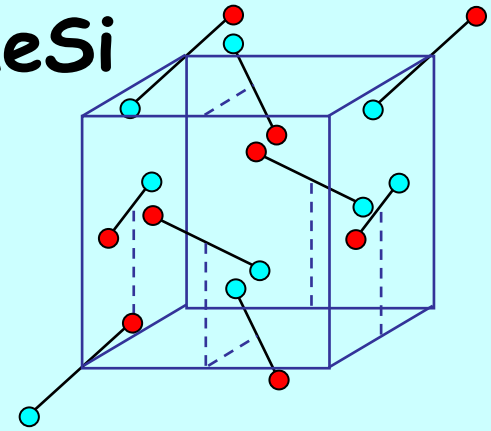
$$H_{EX} = -\frac{1}{2}\sum J_{\mathbf{RR}'}\mathbf{S}_{\mathbf{R}} \cdot \mathbf{S}_{\mathbf{R}'}, \qquad H_{EX} = \frac{1}{2}\sum J_{\mathbf{q}}\mathbf{S}_{\mathbf{q}} \cdot \mathbf{S}_{-\mathbf{q}},$$

Scalar product+vector product=spiral state

$$H_{DM} = \frac{1}{2}\sum D_{\mathbf{RR}'}(\nabla - \nabla')\mathbf{S}_{\mathbf{R}} \times \mathbf{S}_{\mathbf{R}'}, \qquad H_{DM} = \sum iD_{\mathbf{q}}\mathbf{q} \cdot [\mathbf{S}_{\mathbf{q}} \times \mathbf{S}_{-\mathbf{q}}]$$

Heisenberg model rather than itinerant

MeSi



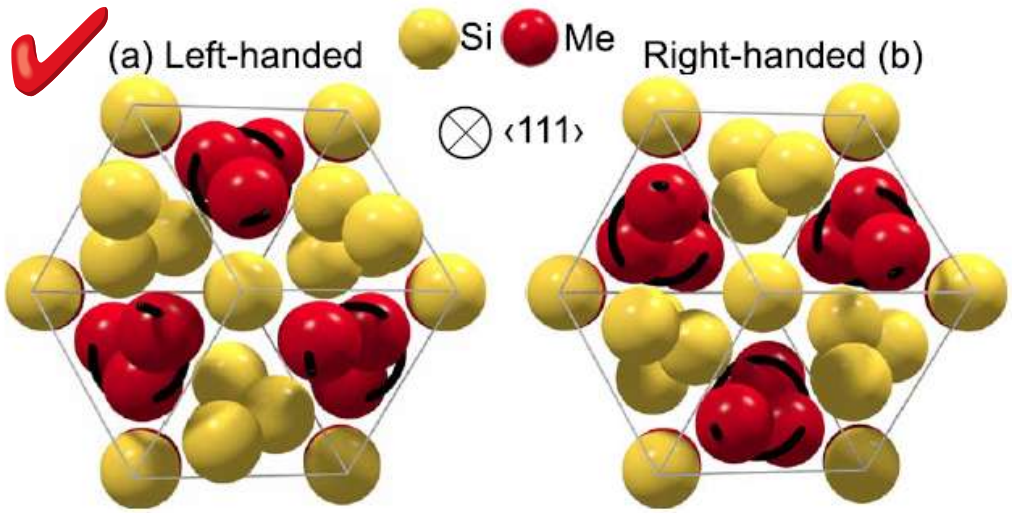
- Me=Mn,Fe
- Si

B20 structure without inversion center
(T^4-$P2_13$)

4 Me atoms in the unit cell with
The crystallographic coordinated

(x,x,x) (1/2+x,1/2-x,-x)
(1/2-x,-x,1/2+x) (-x,1/2+x,1/2-x)
+ 4 Si atoms in equivalent position

$Mn_{1-x}Fe_xSi$ structure



x(Mn)=0.137
x(Si)=0.845
a=0.45655(8) nm

x(Mn)=0.863
x(Si)=0.155
a=0.45642(8) nm

PHYSICAL REVIEW B **81**, 012408 (2010)

S. V. Grigoriev,[1] D. Chernyshov,[2,3] V. A. Dyadkin,[1] V. Dmitriev,[2] E. V. Moskvin,[1] D. Lamago,[4] Th. Wolf,[5] D. Menzel,[6] J. Schoenes,[6] S. V. Maleyev,[1] and H. Eckerlebe[7]
[1]*Petersburg Nuclear Physics Institute, Gatchina, 188300 St. Petersburg, Russia*

I) The magnetic susceptibility obeys an approximate Curie-Weiss law.

II) The Curie constant is related with the band structure around the Fermi surface and is independent of the saturation moment at $T = 0$:

$$S_L^2 = 3\,T N_0^{-2} \sum_q \chi_q$$

$$S_L^2(T_C) = \tfrac{3}{5} \cdot 2\varrho^2(\alpha - 1)/\alpha^2 N_0^2 F_1 = \tfrac{3}{5}[M(0)/N_0]^2$$

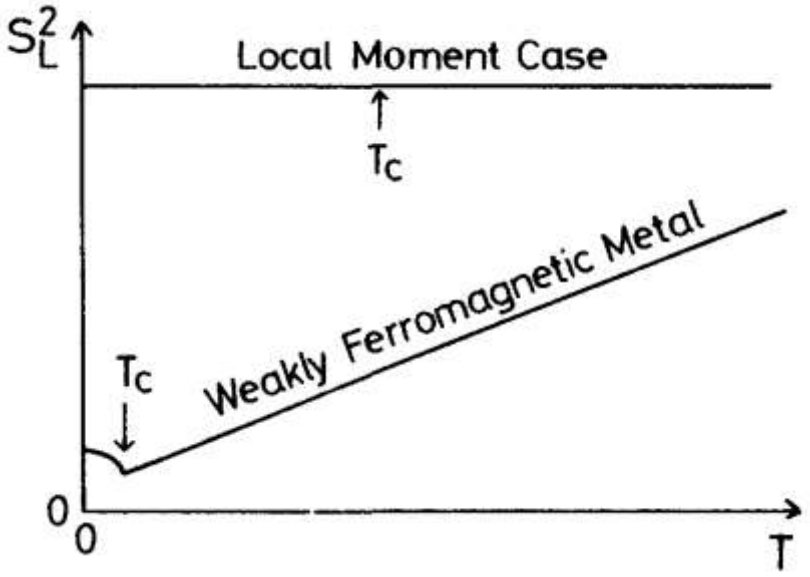
$$S_L^2(T) - S_L^2(T_C) = \frac{3\varrho^3}{5F_1 N_0^2}\frac{1}{\chi} = \frac{3}{5gN_0^2}\frac{1}{\chi}$$

$$\frac{1}{\chi} \approx \tilde{C}^{-1} \cdot (T - T_C)$$

Tôru Moriya

Spin Fluctuations in Itinerant Electron Magnetism

S_L^2 –amplitude of spin fluctuations local spin density



Only $\mu_{sat}(0)$ has physical meaning; it is characteristic of the spin density in the unit cell.

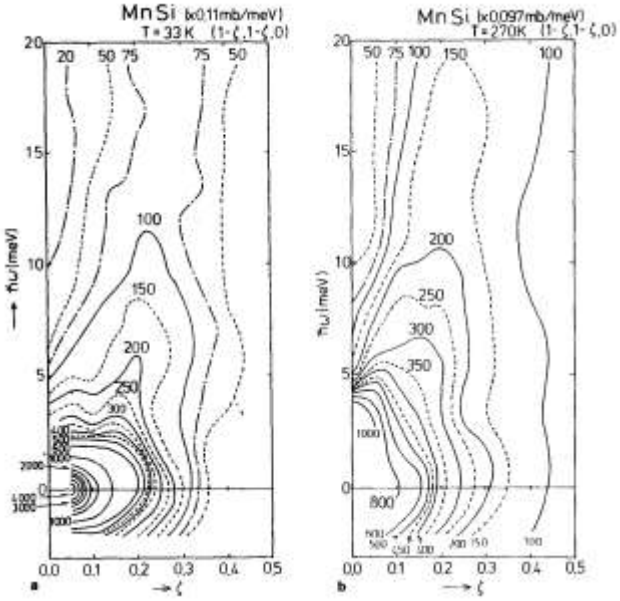
Curie-Weiss constant cannot be interpreted in a classical way and does not tell anything about magnetic moment amplitude.

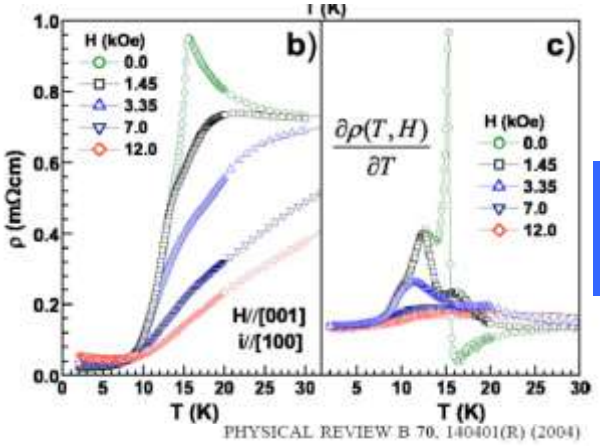
What is really missed… spin polarons!

There are strong spin fluctuations.

MnSi is an archetypical example supporting Moriya theory

Section 5.1 shows that MnSi provides a very good example of weak itinerant ferromagnets and almost complete measurements of $\mathcal{S}(q, \omega)$ were carried out with the results in remarkably good agreement with the SCR theory. No further examples are discussed here, refering to Sect. 5.1 for MnSi as a typical example of weak itinerant ferromagnets. It is gratifying that we have good typical examples in the two extremes where the agreement between theory and experiment is satisfactory.





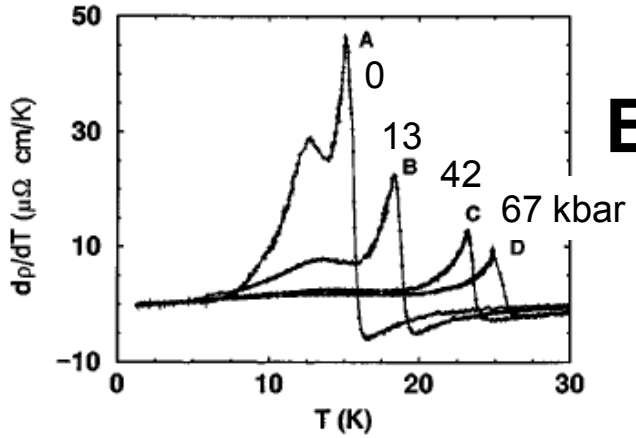
PHYSICAL REVIEW B 70, 140401(R) (2004)

Magnetic polaron and Fermi surface effects in the spin-flip scattering of EuB_6

R. R. Urbano,[1] P. G. Pagliuso,[1] C. Rettori,[1] S. B. Oseroff,[2] J. L. Sarrao,[3] P. Schlottmann,[4] and Z. Fisk[4]

2004

Spin polaron system



EuB_6

1997

PHYSICAL REVIEW B VOLUME 56, NUMBER 22 1 DECEMBER 1997-II

High pressures and ferromagnetic order in EuB_6

J. C. Cooley* and M. C. Aronson
Department of Physics, The University of Michigan, Ann Arbor, Michigan 48109-1120

J. L. Sarrao* and Z. Fisk
National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32306

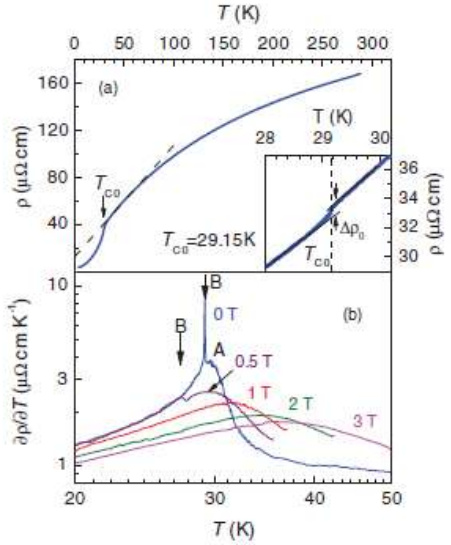
(Received 3 July 1997)

PHYSICAL REVIEW B 85, 045131 (2012)

Magnetic phase diagram of MnSi in the high-field region

S. V. Demishev,* V. V. Glushkov, I. I. Lobanova,† M. A. Anisimov, V. Yu. Ivanov, T. V. Ishchenko, M. S. Karasev, N. A. Samarin, N. E. Sluchanko, V. M. Zimin, and A. V. Semeno

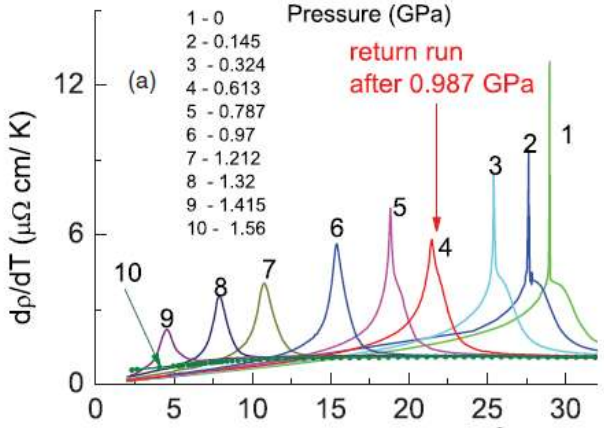
MnSi



2012

Phase diagram of the itinerant helimagnet MnSi from high-pressure resistivity measurements and the quantum criticality problem

Alla E. Petrova and Sergei M. Stishov*



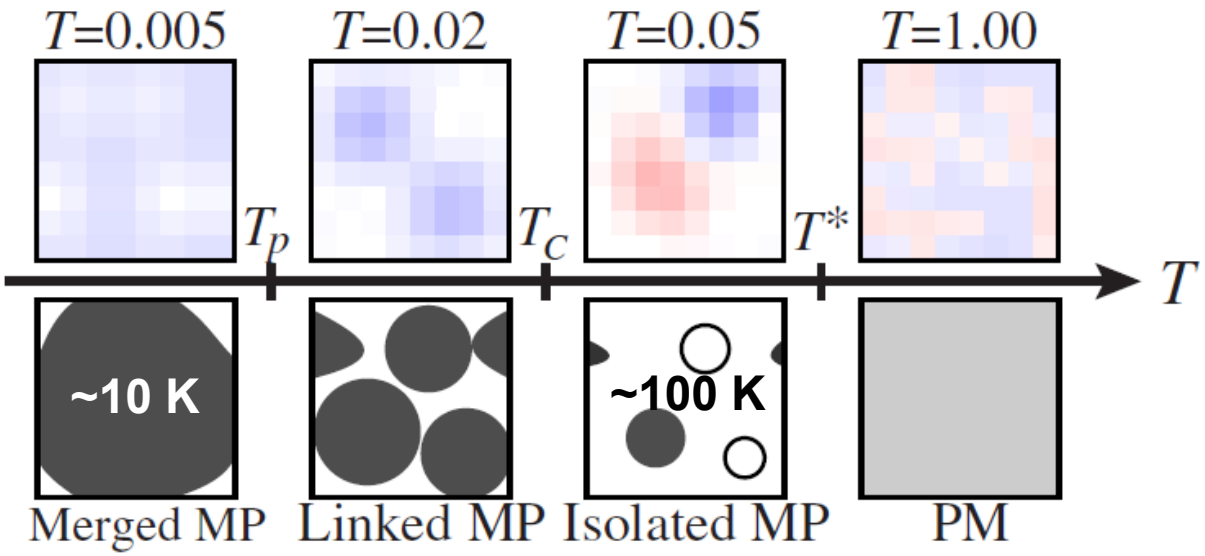
PHYSICAL REVIEW B 74, 094413 (2006)

Magnetic-phase transition in the magnetic-polaron system studied with the Monte Carlo method: Anomalous specific heat of EuB_6

Unjong Yu and B. I. Min

$$H = -t \sum_{\langle i,j \rangle \sigma} (c^{\dagger}_{i\sigma} c_{j\sigma} + \text{H.c.}) - J_H \sum_i \vec{\sigma}_i \cdot \vec{S}_i,$$

Kondo lattice model



Magnetic phases are constructed of spin polarons

Two intermediate magnetic phases

Percolation effects

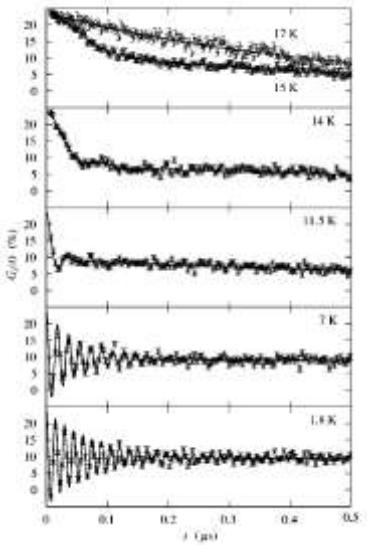
PHYSICAL REVIEW B 70, 020401(R) (2004)

Magnetic phase separation in EuB_6 detected by muon spin rotation

M. L. Brooks,[1] T. Lancaster,[1] S. J. Blundell,[1] W. Hayes,[1] F. L. Pratt,[2] and Z. Fisk[3]

EuB_6

These observations fit in well with the polaron percolation picture for the intermediate temperature range; muons stopping in ferromagnetic regions of overlapping polarons give rise to the oscillating signal, while most muons stop in the intervening paramagnetic regions.

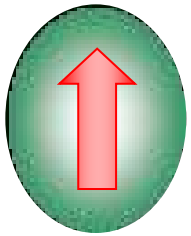


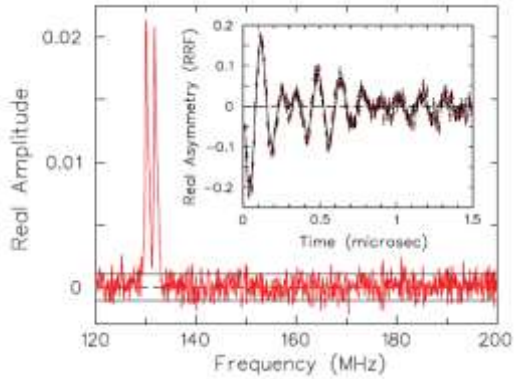
PHYSICAL REVIEW B 83, 140404(R) (2011)

Electron localization into spin-polaron state in MnSi

Vyacheslav G. Storchak,[1,*] Jess H. Brewer,[2] Roger L. Lichti,[3] Thomas A. Lograsso,[4] and Deborah L. Schlagel[4]

MnSi



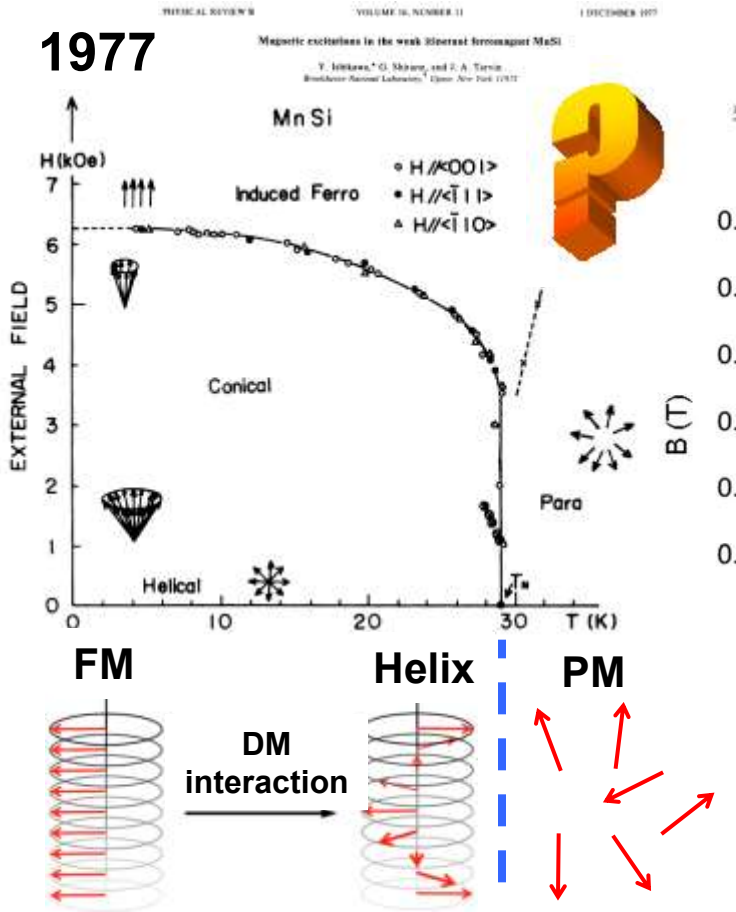


Spin polaron = Ferron

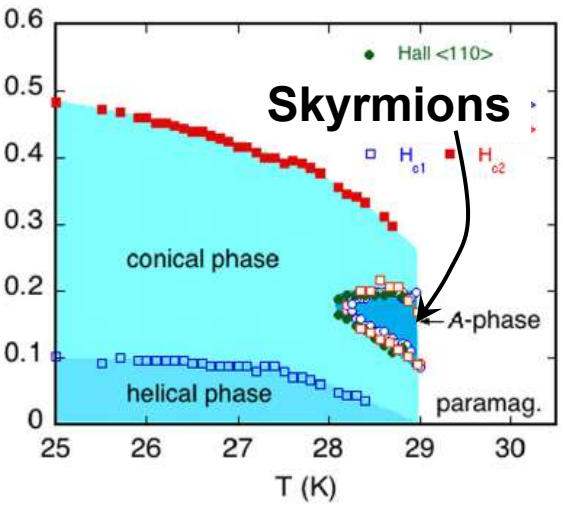
Exists in both paramagnetic and ferromagnetic phases.

$$\mu^* \sim 24\mu_B$$

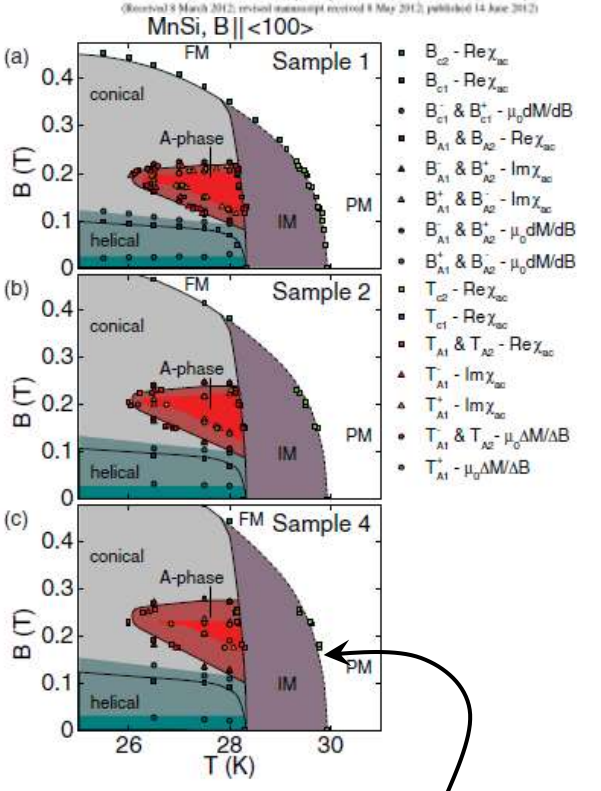
1977



2009



2012



Helix period in MnSi: L=18.5 nm

Substitution by Fe reduces spin helix period. In $Mn_{0.9}Fe_{0.1}Si$ L=10 nm.

Numerous works for low magnetic fields

High field region (B>0.6 T) is not well investigated!

Intermediate phase

С. В. ВОНСОВСКИЙ

МАГНЕТИЗМ

МАГНИТНЫЕ СВОЙСТВА ДИА-, ПАРА-, ФЕРРО-, АНТИФЕРРО-, И ФЕРРИМАГНЕТИКОВ

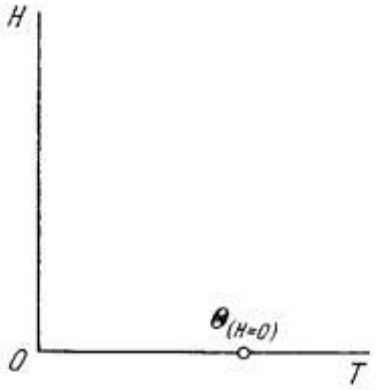


Рис. 18.21. «Линия» (изолированная точка) фазового перехода второго рода на плоскости (H, T).

На плоскости (H, T) (рис. 18.21) наблюдается совсем иная картина. В присутствии поля точка Кюри вообще исчезает как точка фазового перехода, ибо при $H \neq 0$ исчезает скачок в симметрии, так как под влиянием поля намагниченность остается и при $T > \Theta$. Поэтому на плоскости (H, T) точка Кюри является *изолированной* точкой, лежащей на оси T при $T = \Theta$ $(p)_{\langle H=0 \rangle}$ [см. [9], Вонсовский и Шур (1948), [83, 222]].

ИЗДАТЕЛЬСТВО «НАУКА»
ГЛАВНАЯ РЕДАКЦИЯ
ФИЗИКО-МАТЕМАТИЧЕСКОЙ ЛИТЕРАТУРЫ
МОСКВА 1971

In magnetic field the transition P – FM is not sharp and acquires crossover character.

Not true for MnSi…

PHYSICAL REVIEW B VOLUME 30, NUMBER 1 1 JULY 1984

Mössbauer study of $Mn_{1-x}Fe_xSi$ in external magnetic fields

Y. Nishihara, S. Waki, and S. Ogawa*
Electrotechnical Laboratory, Sakura, Ibaraki 305, Japan
(Received 11 October 1983; revised manuscript received 5 March 1984)

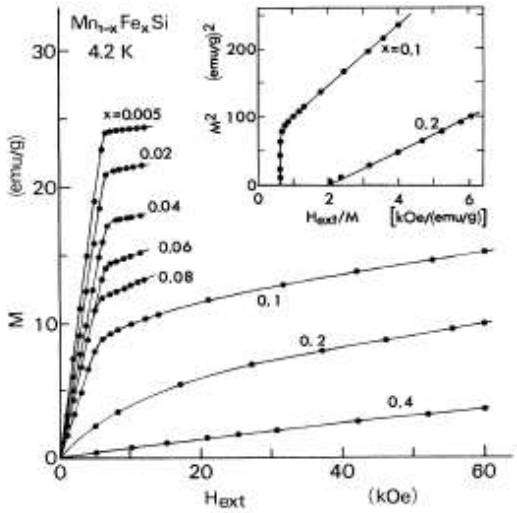


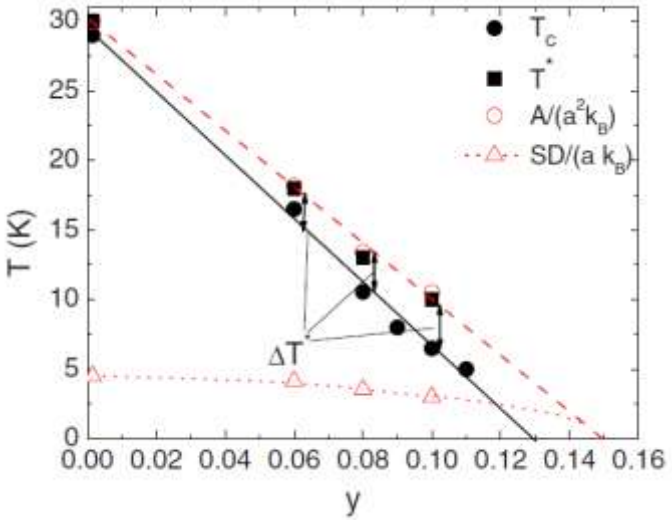
FIG. 1. Magnetization curves of $Mn_{1-x}Fe_xSi$ at 4.2 K.

1984:
Disappearance of spontaneous magnetic moment between x=0.1 and x=0.2

PHYSICAL REVIEW B 79, 144417 (2009)

Helical spin structure of $Mn_{1-y}Fe_ySi$ under a magnetic field: Small angle neutron diffraction study

S. V. Grigoriev,[1] V. A. Dyadkin,[1] E. V. Moskvin,[1,2] D. Lamago,[3,4] Th. Wolf,[4] H. Eckerlebe,[5] and S. V. Maleyev[1]



2009:
Curie temperature is expected to turn to zero at x*~0.13: $T_c(x^*)=0$.

Nature of the magnetic properties of MnSi and $Mn_{1-x}Fe_xSi$

Itinerant magnets vs. Heisenberg localized magnetic moments

Spin polarons

Exotic spin states (skyrmions).

Magnetic phase diagram in the high field region.

Problem of the sharp phase boundaries

Quantum critical behavior (quantum bicriticality)

Underlying quantum critical point

Experimental tools:

Transport properties, magnetization, electron spin resonance

CENSORED

65+

PHYSICAL REVIEW B 75, 115111 (2007)

Spin dynamics in a weakly itinerant magnet from ^{29}Si NMR in MnSi

M. Corti,[1] F. Carbone,[2] M. Filibian,[1] Th. Jarlborg,[2] A. A. Nugroho,[3] and P. Carretta[1]

metals). The corresponding magnetic moment at the minimum was estimated to be $0.75\mu_B$ per formula unit. Almost all of the spin polarization is on the Mn ion, while on the Si ion the polarization is of opposite sign. The magnitude of the

the experimental one (a=4.55 Å) (Fig. 5).

LDA calculations

On the other hand, if the real lattice parameter is considered, LDA calculations give a local moment of about $1.2\mu_B$ per MnSi, much larger than the one experimentally determined. Often,[6,11] the lattice parameter is tuned in the calculation in order to match the experimentally determined

Skyrmion tale

И терпентин на что-нибудь полезен!
К.Прутков

Contribution to the theory of inhomogeneous states of magnets in the region of magnetic-field-induced phase transitions. Mixed state of antiferromagnets

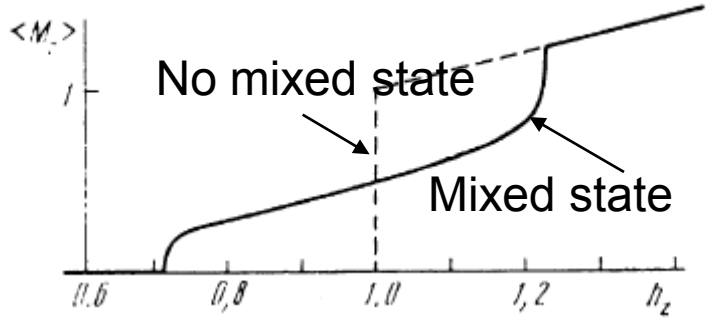
A. N. Bogdanov and D. A. Yablonskiĭ

Zh. Eksp. Teor. Fiz. **96**, 253–260 (July 1989)

We demonstate the existence of an extensive group of easy-axis antiferromagnets in which an inhomogeneous state similar to the mixed states of type-II superconductors is realized in a wide range of fields and angles. A phenomenological theory of the mixed state in easy-axis antiferromagnets is developed.

Crystals without inversion center!

Formation of inhomogeneous state (analogue to superconductors with σ<0) in vicinity of spin-flop transition.



sotropy in the basal plane. It was shown in Ref. 22 that in easy-axis ferromagnets without inversion center, with symmetry higher than rhombic, a system of non-interacting vortices has in a definite field interval a lower energy compared with the homogeneous state and a spiral structure. We em-

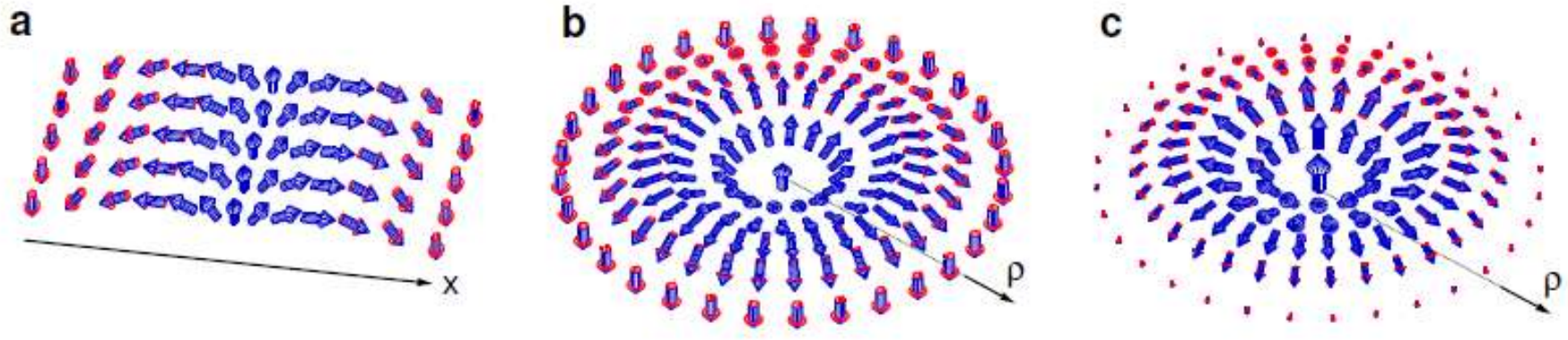
In the old times mixed state was thought to consist of Abrikosov-type vortixes.

[22] A. N. Bogdanov and D. A. Yablonskiĭ, Zh. Eksp. Teor. Fiz. **95**, 178 (1989) [Sov. Phys. JETP **68**, 101 (1989)].

Nowadays "mixed" state is a skyrmion lattice state. Skyrmion is a kind of knot in the magnetization vector field.

Theorists can imagine different types of skyrmions…

Simple case:



Texture propagating along x

Skyrmion with |**m**|=const

Skyrmion with $|m(\rho\to\infty)|\to 0$

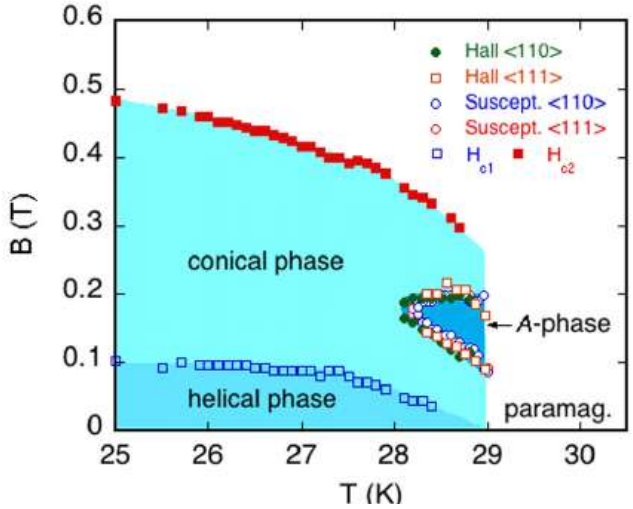
In experiments with skyrmions visualization a skyrmion lattice is observed
Do people see real skyrmion lattice or just superposition of textures with different propagation vectors???

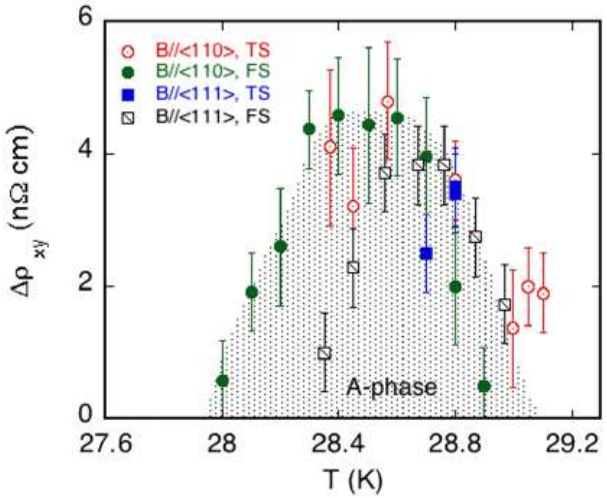
PRL 102, 186602 (2009) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 8 MAY 2009

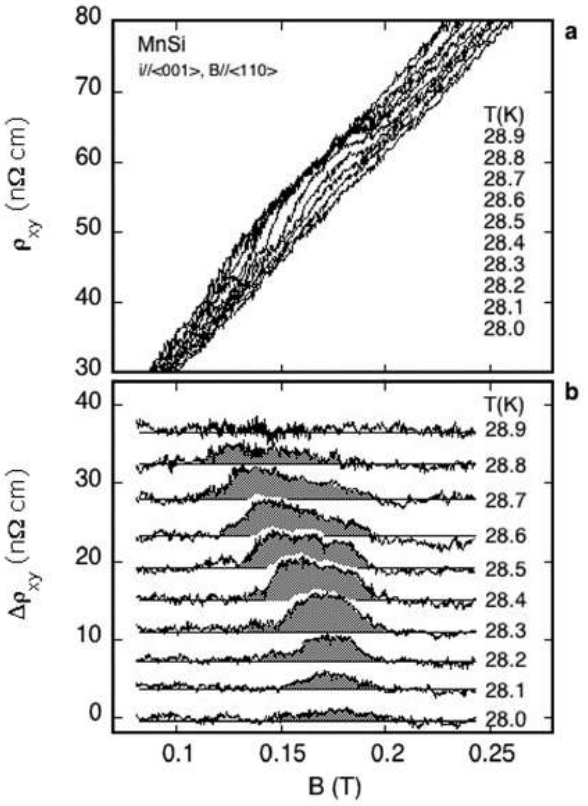
Skyrmions: what for?

Topological Hall Effect in the *A* Phase of MnSi

A. Neubauer,[1] C. Pfleiderer,[1] B. Binz,[2] A. Rosch,[2] R. Ritz,[1] P. G. Niklowitz,[1] and P. Böni[1]







Topological Hall effect (THE) in A-phase of MnSi

2010: A year of skyrmions ($Fe_{1-x}Co_xSi$ films + Lorentz TEM)

nature

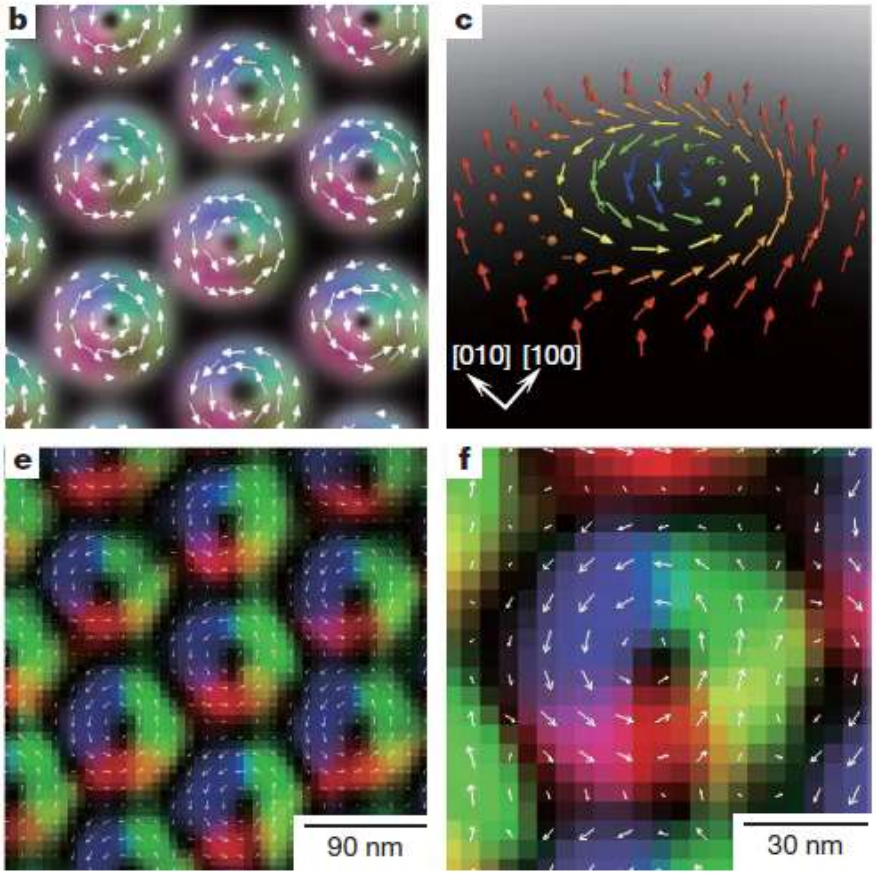
LETTERS

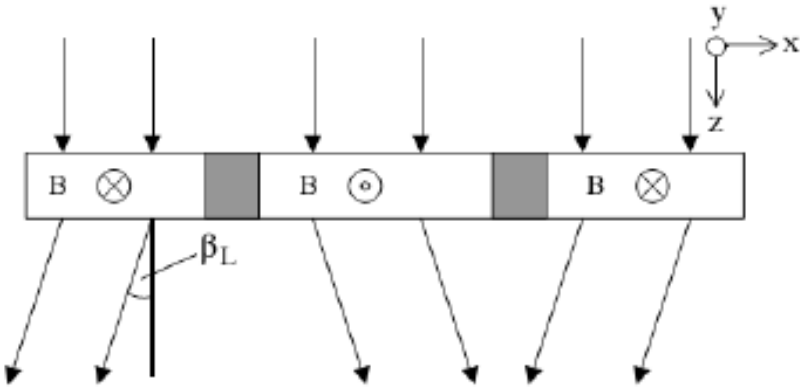
Real-space observation of a two-dimensional skyrmion crystal

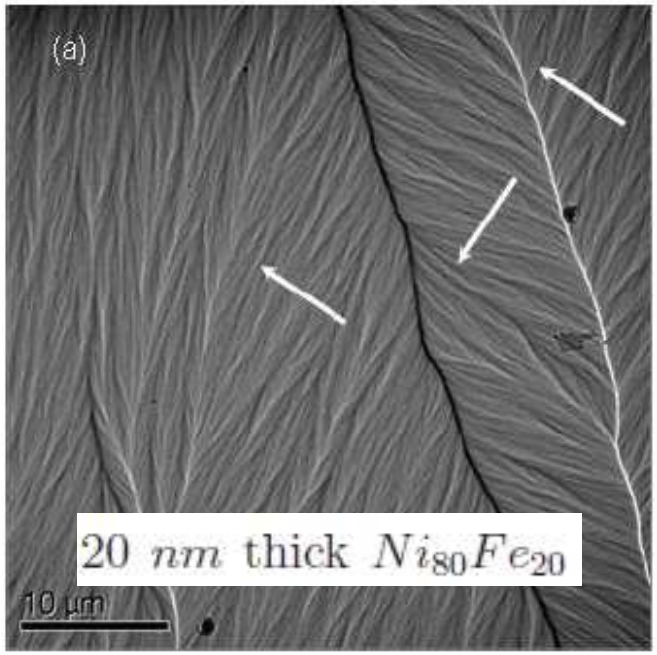
X. Z. Yu[1,2], Y. Onose[2,3], N. Kanazawa[3], J. H. Park[4], J. H. Han[4], Y. Matsui[1], N. Nagaosa[3,5] & Y. Tokura[2,3,5]

Vol 465|17 June 2010|doi:10.1038/nature09124

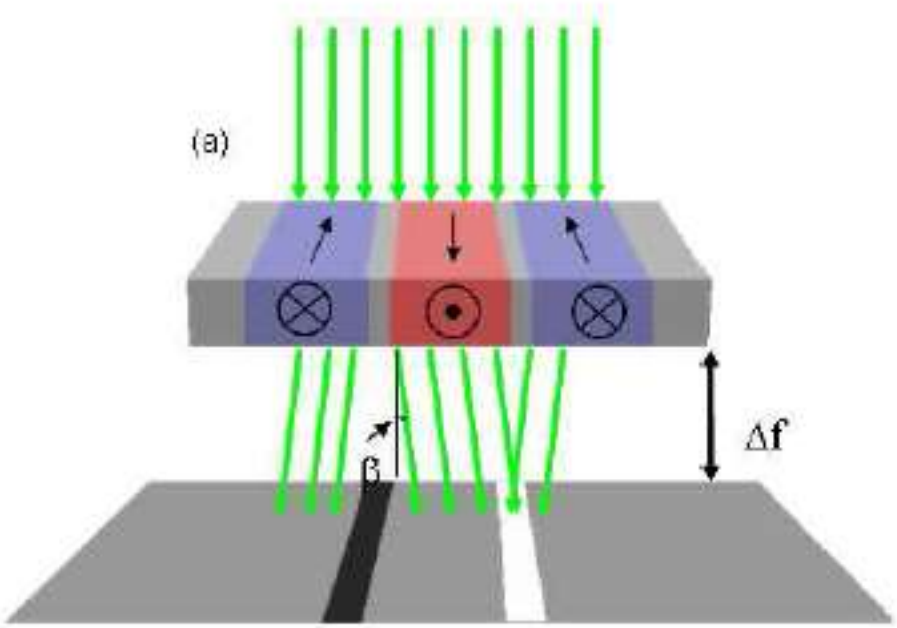
For the skyrmions observed by Yu *et al.*[1], the magnetization is twisted smoothly such that it is antiparallel between the centre and the edges of each skyrmion (Fig. 1). This pattern turns out to be a stable magnetic knot: it cannot be untied as long as the magnetization remains smooth and finite. Skyrmions are therefore classified as topologically stable — a characteristic drawn from the mathematical discipline of topology, which classifies geometric configurations according to properties, such as the winding number, that are robust against all small distortions or perturbations.







Domain structure in Lorentz TEM



The contrast is due to deflection of the electrons by local magnetic fields.

Somehow out of focus… Blurred image is unavoidable.

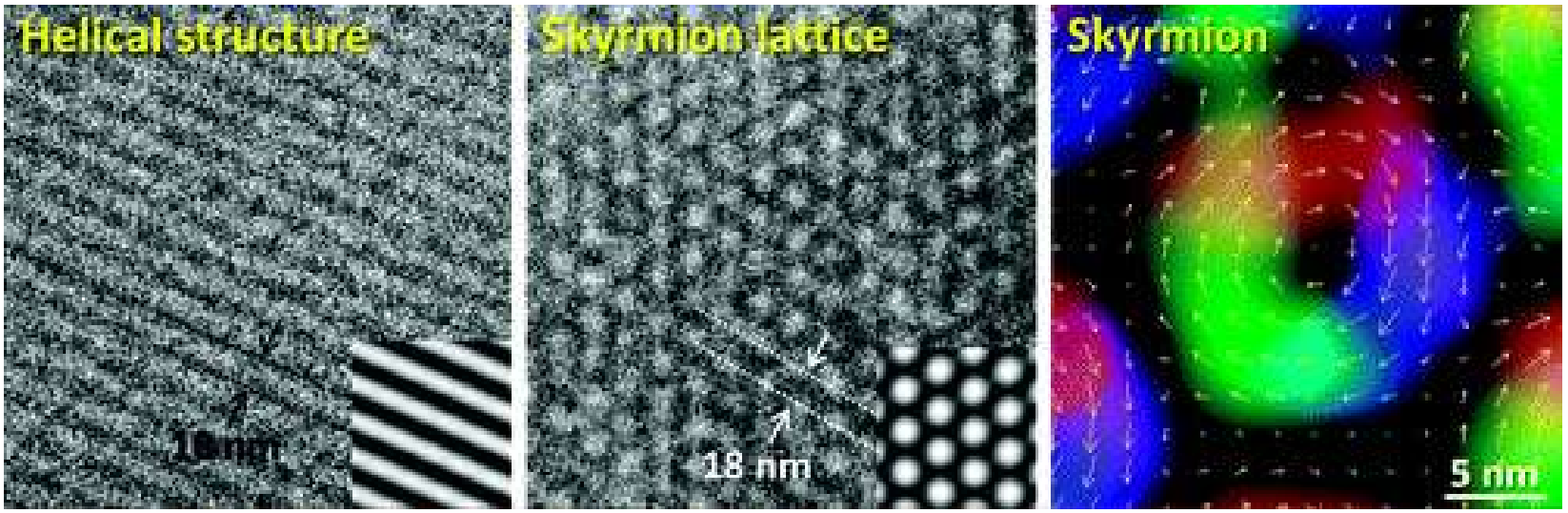
One of two methods to examine magnetic structure at nanoscale.

Thin films only!

2012: Visualization of skyrmions ion MnSi

A. Tonomura et al., Nano Lett., **12,** 1673 (2012).

MnSi thin films obtained from single crystal + Lorentz TEM



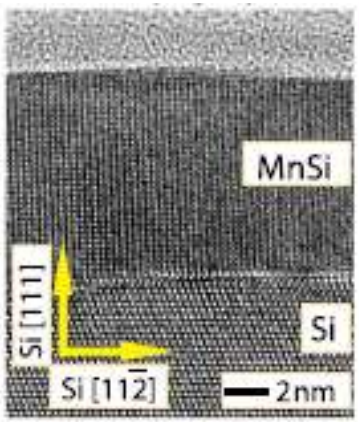
Skyrmion lattice observed in A-phase. No direct evidence for single skyrmions.

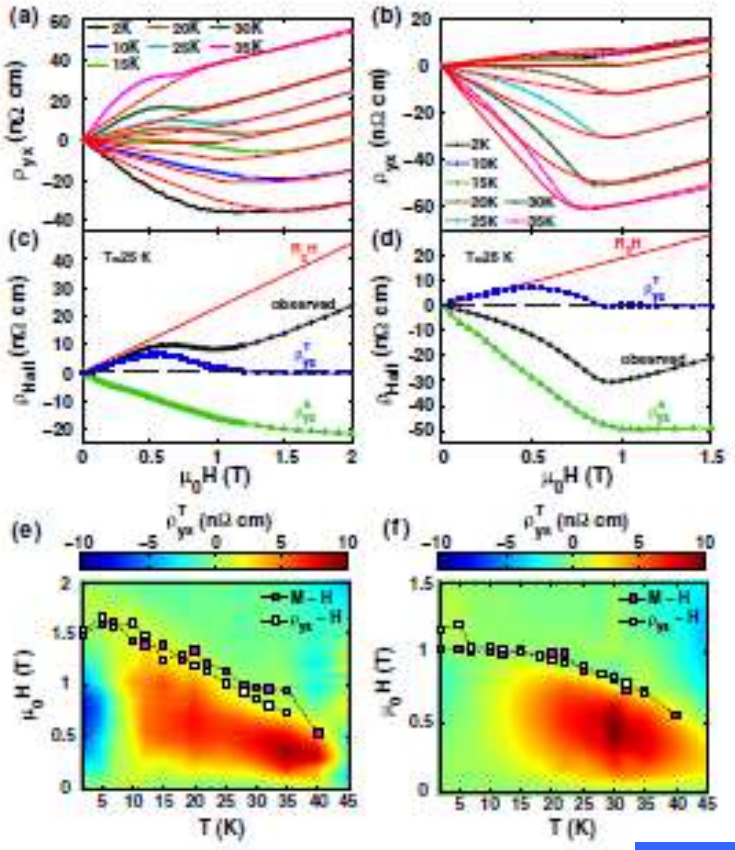
A-phase is a tiny region on H-T magnetic phase diagram. So skyrmions appears as very delicate creatures. How about robust formation and analogy with superconductors mixed state?

PRL 110, 117202 (2013) PHYSICAL REVIEW LETTERS week ending 15 MARCH 2013

Robust Formation of Skyrmions and Topological Hall Effect Anomaly in Epitaxial Thin Films of MnSi

Yufan Li,[1,2] N. Kanazawa,[1] X. Z. Yu,[3] A. Tsukazaki,[1] M. Kawasaki,[1,3] M. Ichikawa,[1] X. F. Jin,[2] F. Kagawa,[1] and Y. Tokura[1,3]



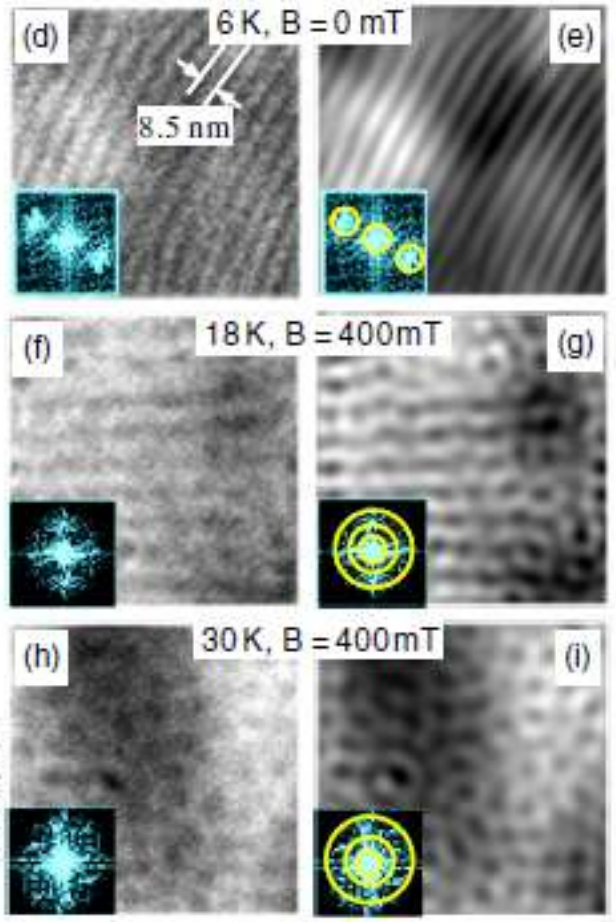


Progress in thin film technology!

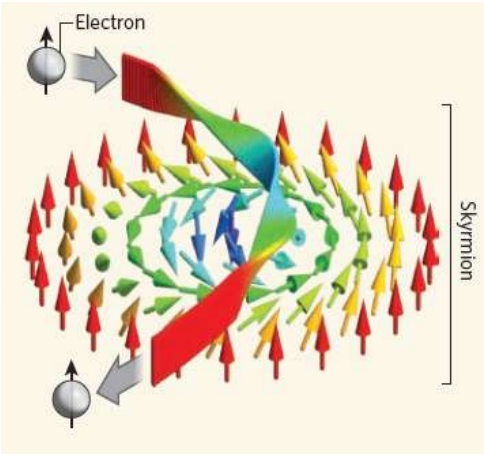
Enhancement of THE.

More "robust" case?

Disorder in skyrmion lattice



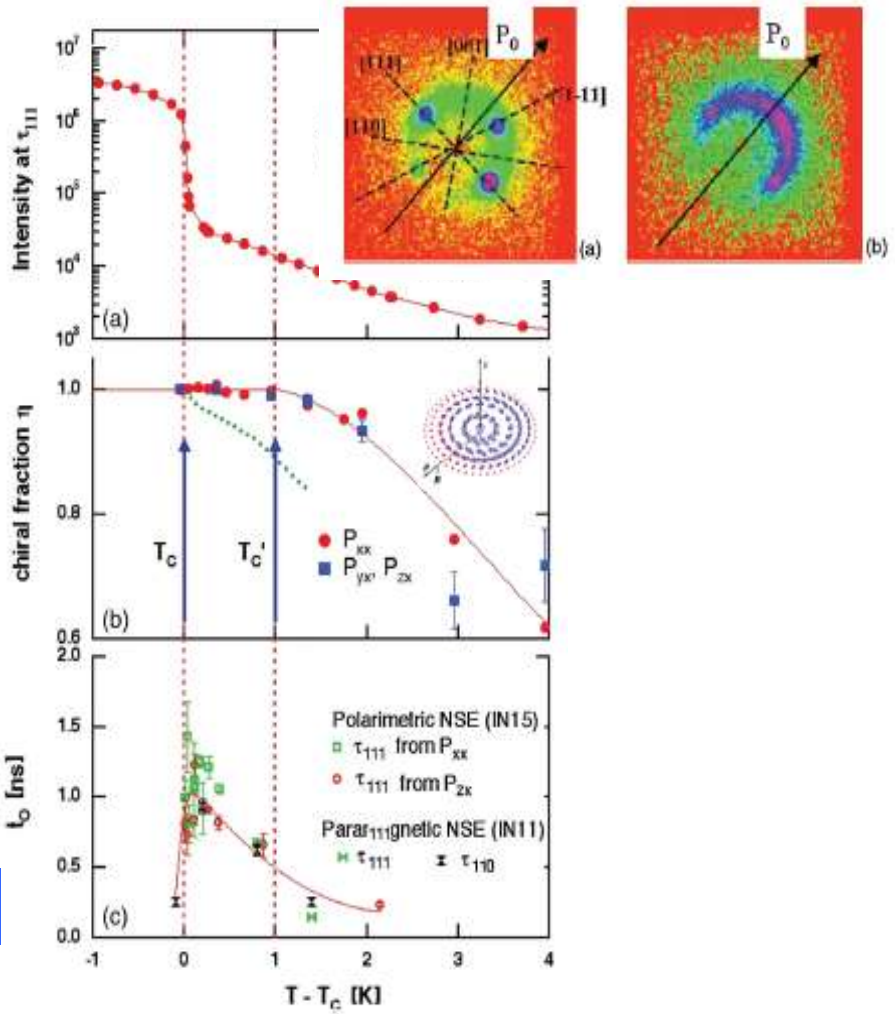
Skyrmions develops in THE area.



PRL 102, 197202 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Chiral Paramagnetic Skyrmion-like Phase in MnSi

C. Pappas,[1,2] E. Lelièvre-Berna,[3] P. Falus,[3] P. M. Bentley,[3] E. Moskvin,[1,4] S. Grigoriev,[4] P. Fouquet,[3] and B. Farago[3]



2D case OK. How about 3D?

A-phase in MnSi. Is it possible to observe melting of the skyrmion lattice (if any)?

Any other effects apart THE, which may serve as the evidence of skyrmions?

Skyrmions and (or vs) spin polarons?

ESR, magnetic phase diagram and itinerant magnetism

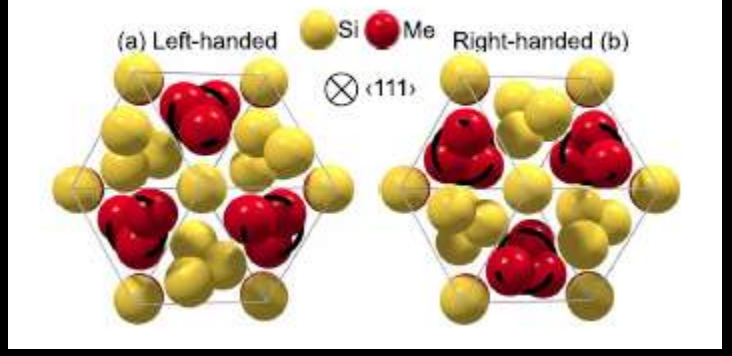
Если на клетке слона прочтёшь надпись "буйвол", не верь глазам своим.
К.Прутков

New technique of cavity measurements

Magnetization data

Magnetoresistance and resistivity data

Magnetic resonance in MnSi



Absolute calibration of cavity absorption in the units of effective magnetic permeability

Line shape analysis

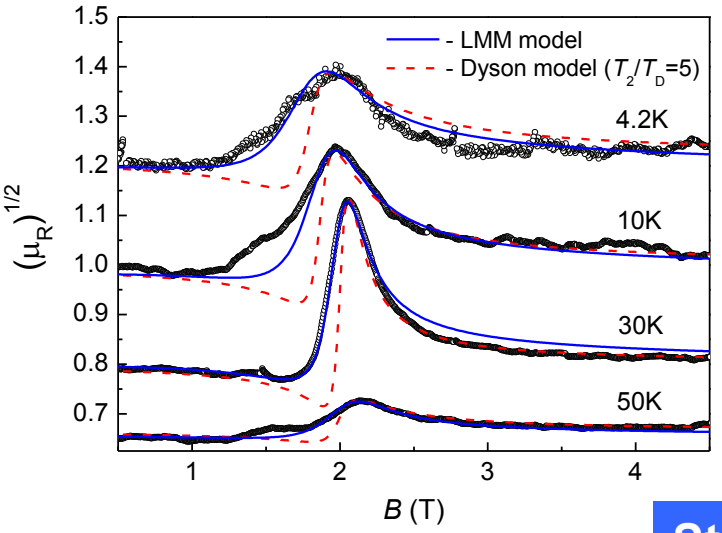
Dysonian analysis

Localized magnetic moments (LMMs) model

Moving LMMs v.s. Spatially localized LMMs

Finding spectroscopic parameters: oscillating magnetization M_{osc}, *g*-factor and line width (relaxation parameter)

Absolute calibration in 60 GHz cavity experiment

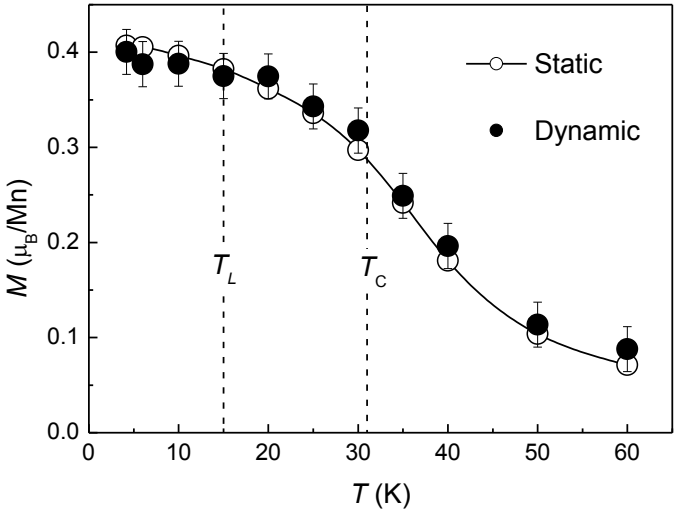


Dysonian analysis suggests negligible spin diffusion.

Magnetic resonance "sees" oscillating magnetic dipoles as localized magnetic moments.

How about itinerant magnetism? Where are spin fluctuations?

Static and dynamic magnetizations



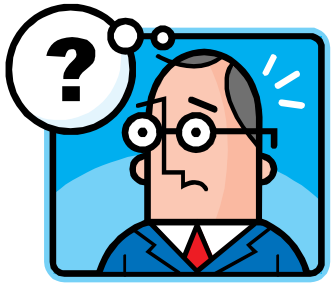
$$\frac{M_{\mathrm{Pauli}}}{M_{\mathrm{Mn}}} \sim \frac{3}{2}\frac{n_e\mu_e^2}{Ck_B}\frac{k_B(T-T_c)}{E_{F0}}\frac{m^*}{m_0} \qquad (T > T_c)$$

and

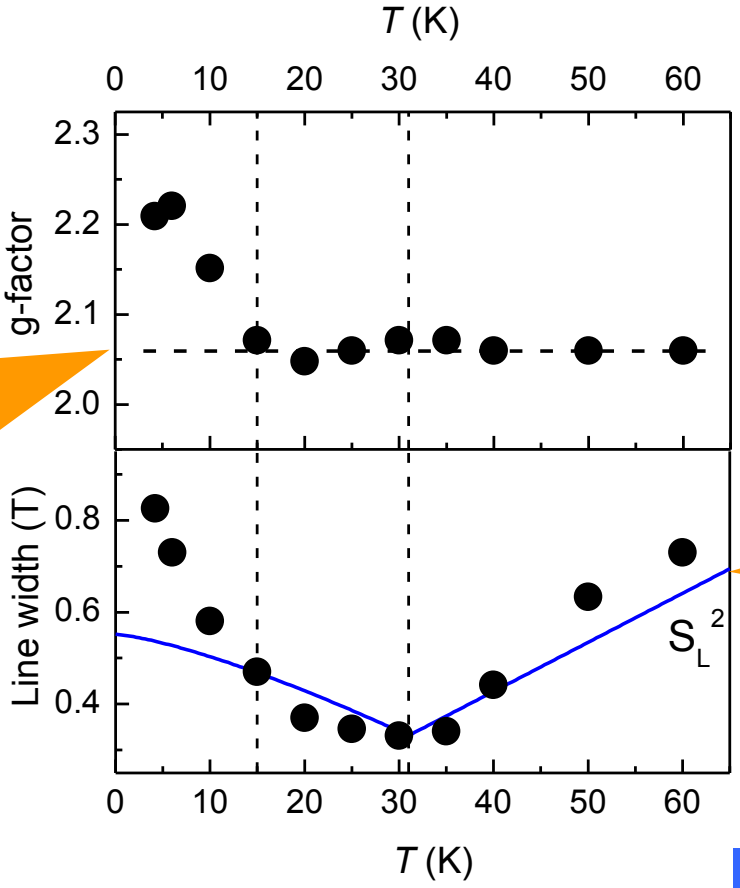
$$\frac{M_{\mathrm{Pauli}}}{M_{\mathrm{Mn}}} \sim \frac{3}{2}\frac{n_e}{n_{\mathrm{Mn}}}\left(\frac{\mu_e}{\mu_{\mathrm{Mn}}}\right)\frac{\mu_e B_{\mathrm{res}}}{E_{F0}}\frac{m^*}{m_0} \qquad (T < T_c).$$

$$M_{\mathrm{Pauli}}/M_{\mathrm{Mn}} \sim 10^{-3}$$

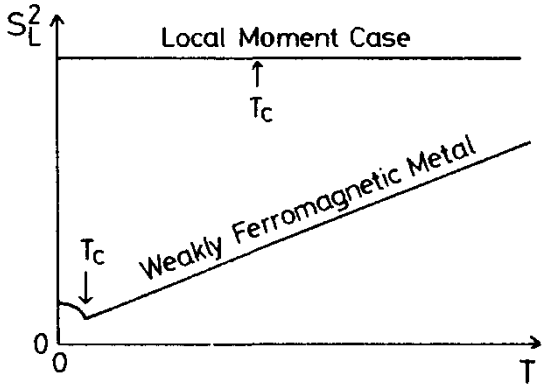
Both itinerant and localized magnetic moments models are consistent with the M(T) experimental data



g-factor temperature dependence is consistent with Heisenberg LMMs. Nothing itinerant.



Itinerant case vs. LMMs



Spin fluctuations may define ESR line width

2011: JETP Letters,**93(4)**
2012: PRB, **85**

ISSN 0021-3640, JETP Letters, 2011, Vol. 93, No. 4, pp. 213–218. © Pleiades Publishing, Inc., 2011.
Original Russian Text © S.V. Demishev, A.V. Semeno, A.V. Bogach, V.V. Glushkov, N.E. Sluchanko, N.A. Samarin, A.L. Chernobrovkin, 2011, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2011, Vol. 93, No. 4, pp. 231–237.

Is MnSi an Itinerant-Electron Magnet? Results of ESR Experiments

S. V. Demishev*, A. V. Semeno, A. V. Bogach, V. V. Glushkov, N. E. Sluchanko, N. A. Samarin, and A. L. Chernobrovkin
A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, Moscow, 119991 Russia
* *e-mail: demis@lt.gpi.ru*
Received October 15, 2010; in final form, January 20, 2011

PHYSICAL REVIEW B 85, 045131 (2012)

Magnetic phase diagram of MnSi in the high-field region

S. V. Demishev,* V. V. Glushkov, I. I. Lobanova,† M. A. Anisimov, V. Yu. Ivanov, T. V. Ishchenko, M. S. Karasev, N. A. Samarin, N. E. Sluchanko, V. M. Zimin, and A. V. Semeno
A. M. Prokhorov General Physics Institute of the RAS, 38 Vavilov Street, 119991 Moscow, Russia
(Received 26 December 2011; published 30 January 2012)

Magnetic phase diagram for B>0.6T

The only one paper

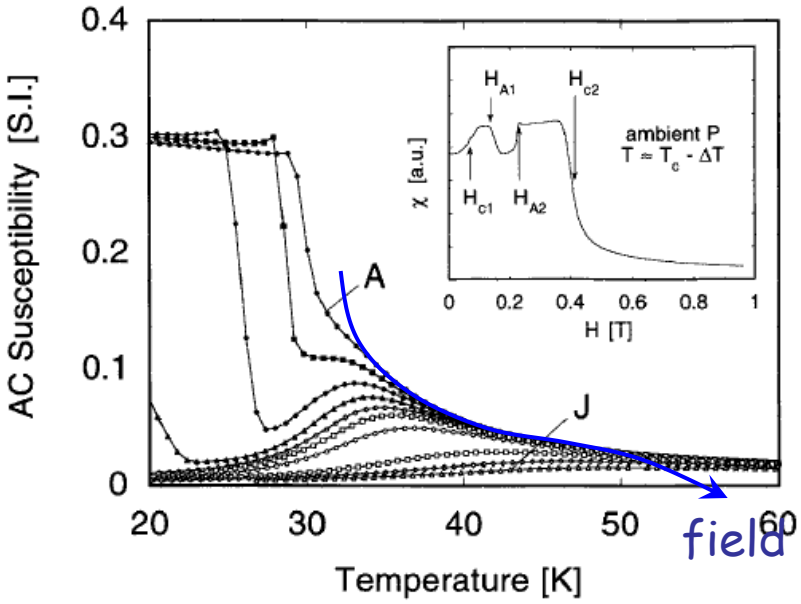
Data up to 1 T only

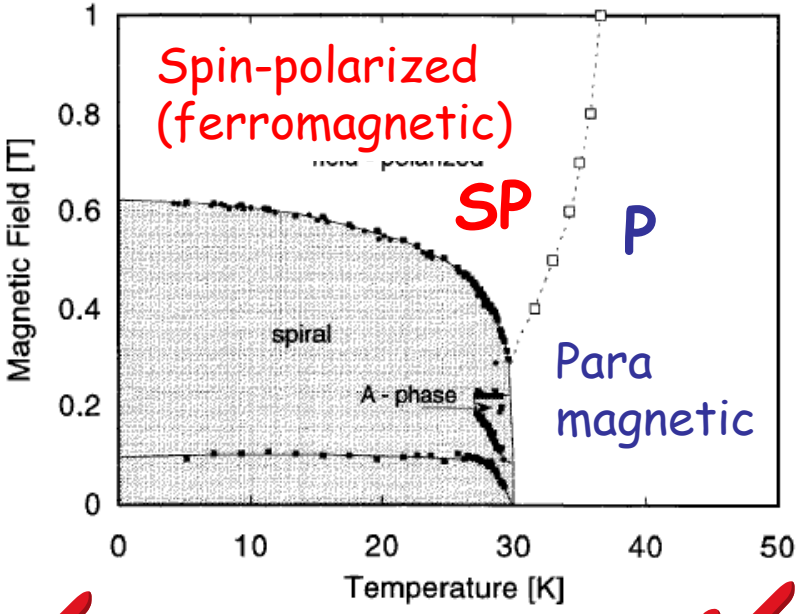
Phase boundary with positive slope

J. Phys.: Condens. Matter 9 (1997) 6677–6687.

Field dependence of the magnetic quantum phase transition in MnSi

C Thessieu, C Pfleiderer†, A N Stepanov and J Flouquet
DRFMC-SPSMS, CEA Grenoble, 38054 Grenoble Cédex 9, France

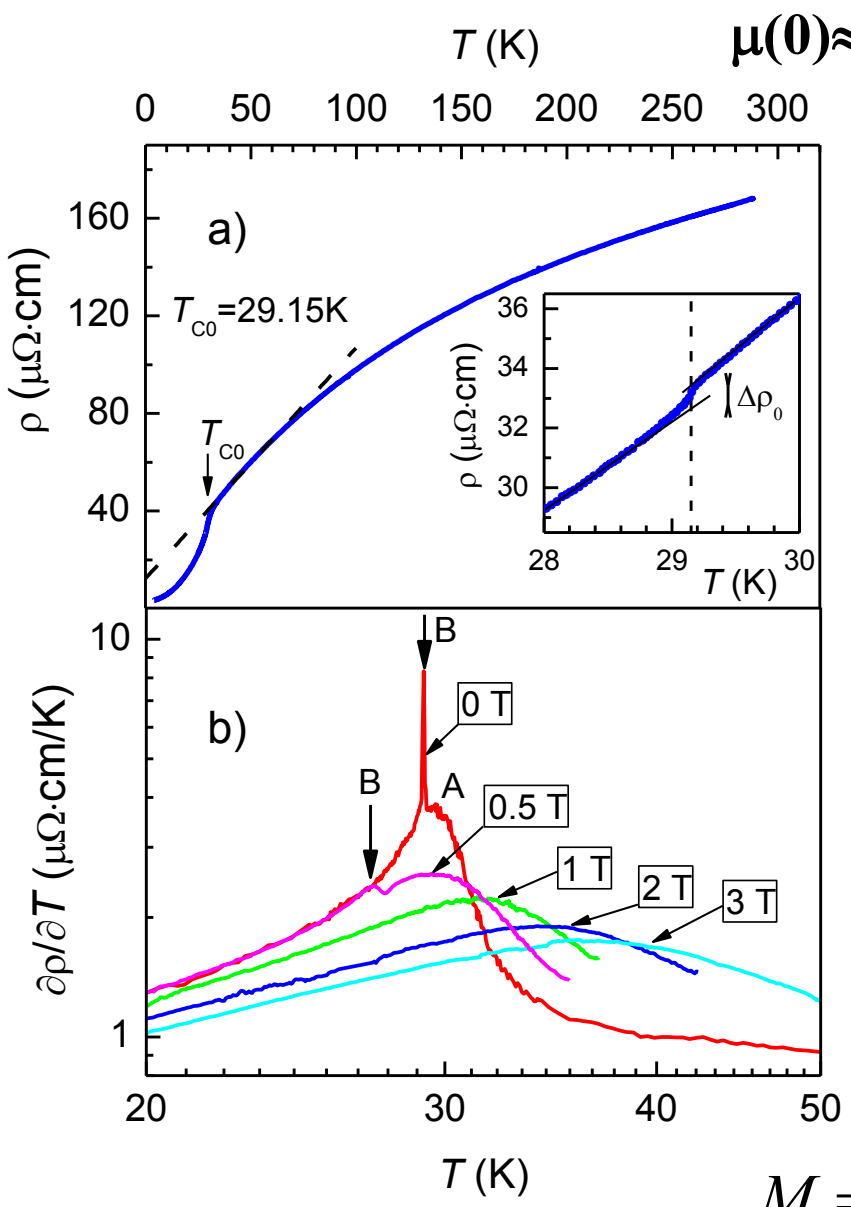


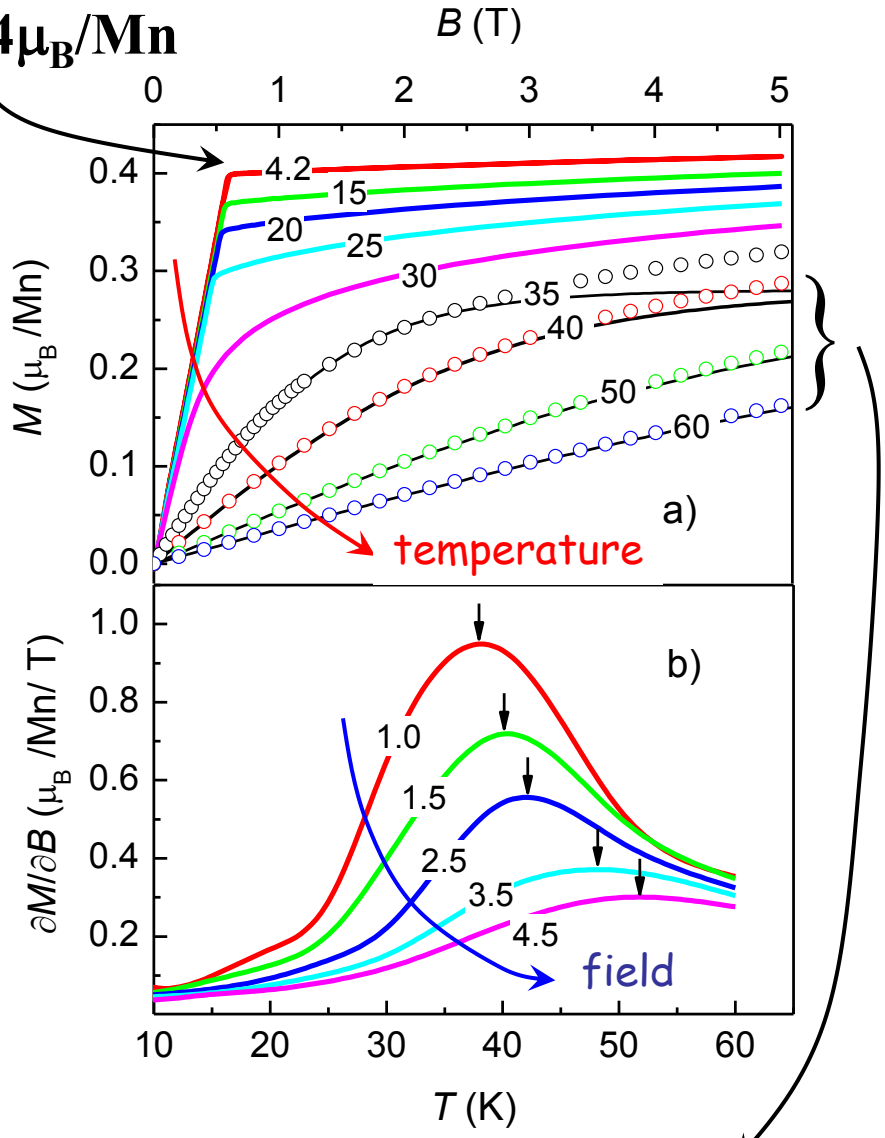


SP-P phase boundary corresponds to magnetic susceptibility maximum

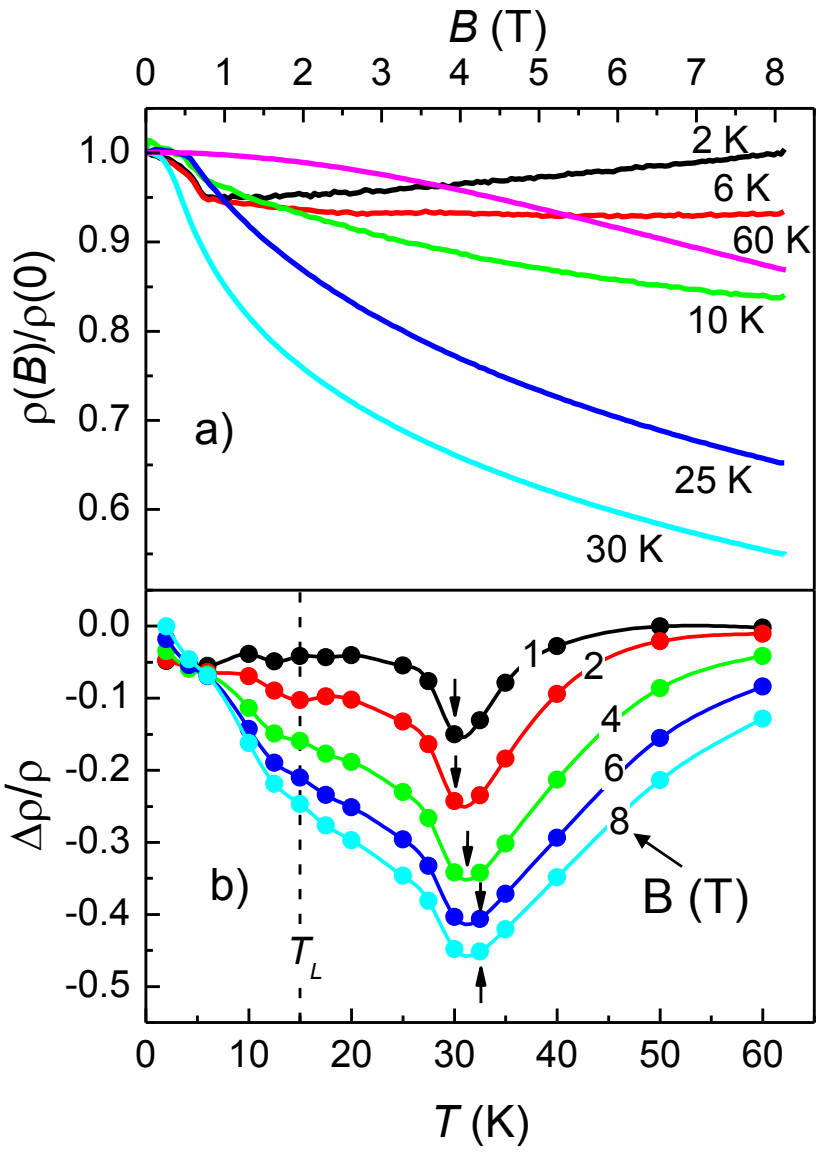
Phase transition is broad (crossover phenomenon?)

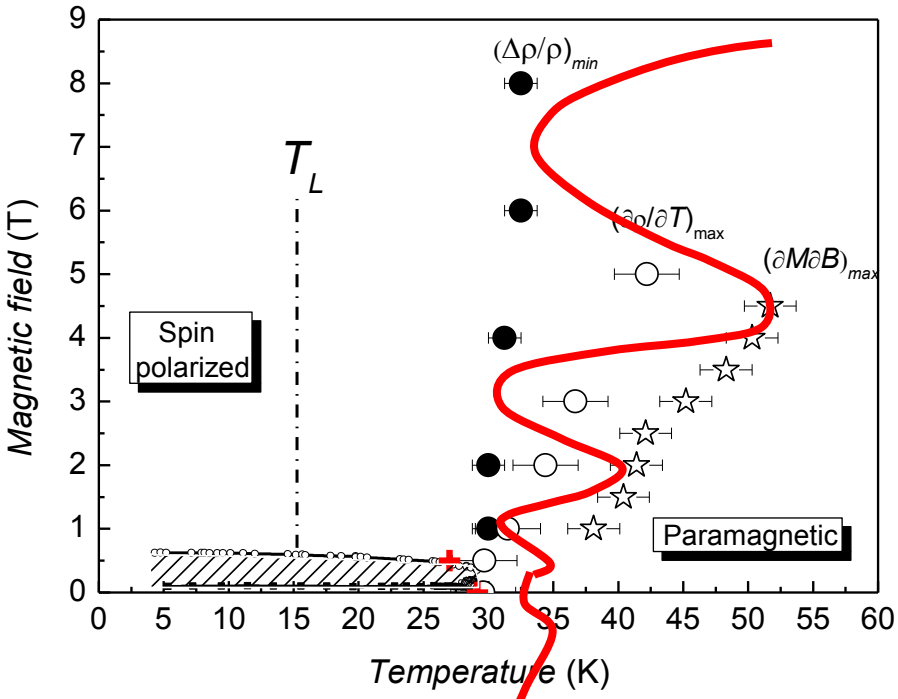
$\mu(0)\approx 0.4\mu_B/Mn$



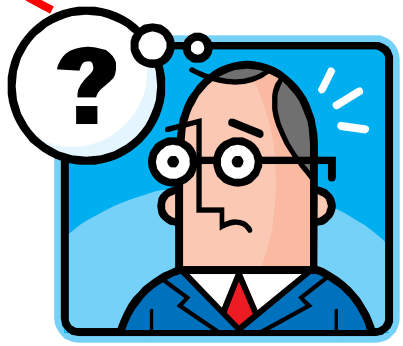


$$M = M_\infty \tanh[\mu^* B / k_B (T - T_c)]; T > T_c$$



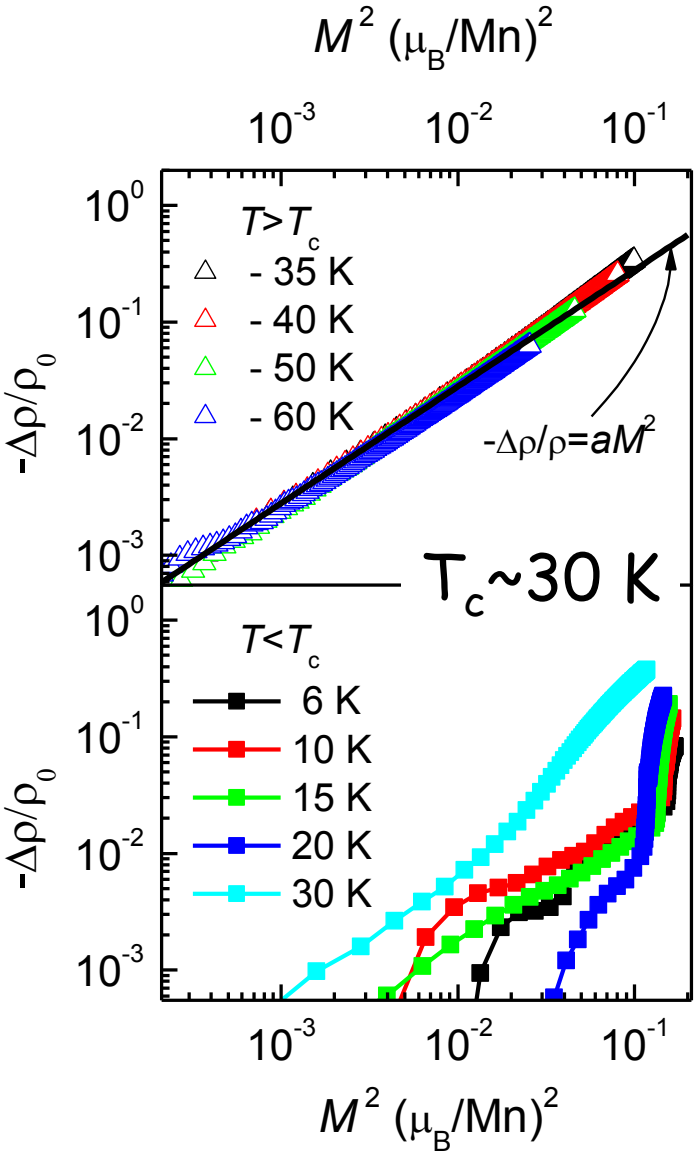


Where is phase boundary?



Low temperature anomaly at T_L~15K

Strong negative magnetoresistance is observed in MnSi



Negative magnetoresistance due to scattering on localized magnetic moments (s-d exchange model)
K. Yosida, 1957

$$\Delta\rho/\rho = -a_0(S,y)(M/M_\infty)^2,$$
$$y \sim (J_0/V_0)^2$$

Universal scaling in paramagnetic state

No universal scaling in magnetically ordered phase (magnetic scatters are no longer independent)

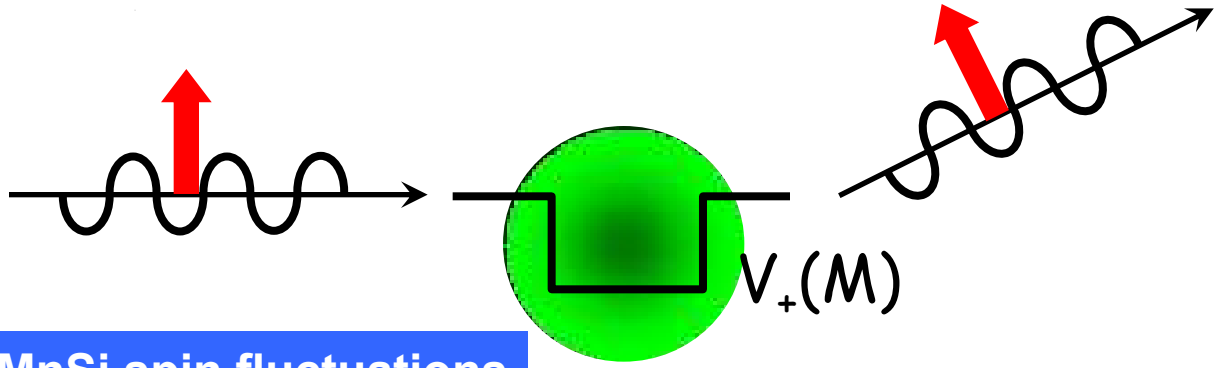
In ferromagnetic phase spins are polarized and Yosida's mechanism is not effective

Magnetoresistance minimum corresponds to sharp SP-P phase boundary at Tc~30-31 K

PHYSICAL REVIEW VOLUME 107, NUMBER 2 JULY 15, 1957

Anomalous Electrical Resistivity and Magnetoresistance Due to an *s-d* Interaction in Cu-Mn Alloys

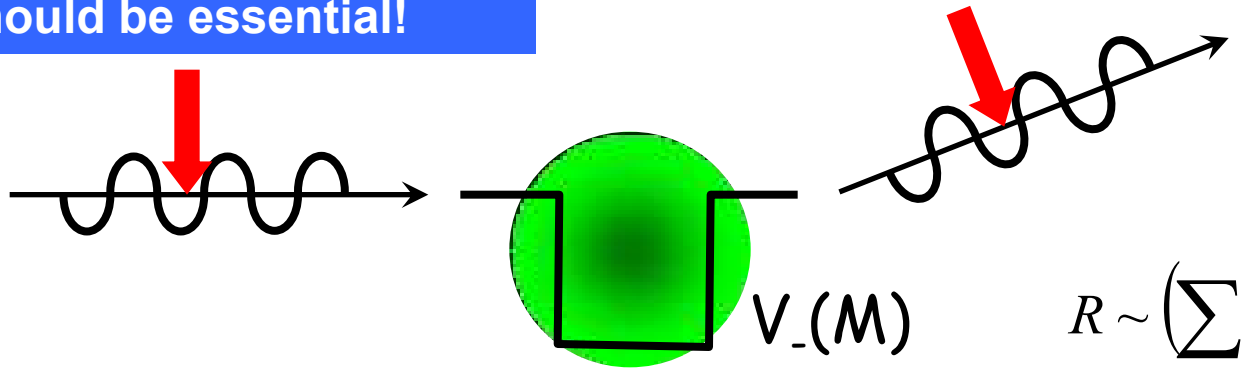
KEI YOSIDA*
Department of Physics, University of California, Berkeley, California
(Received April 8, 1957)



Magnetic ions with magnetization

$$M$$

In MnSi spin fluctuations should be essential!



Spin dependent scattering probability

$$W_{\pm} = W_0 \pm wM$$

Resistivity

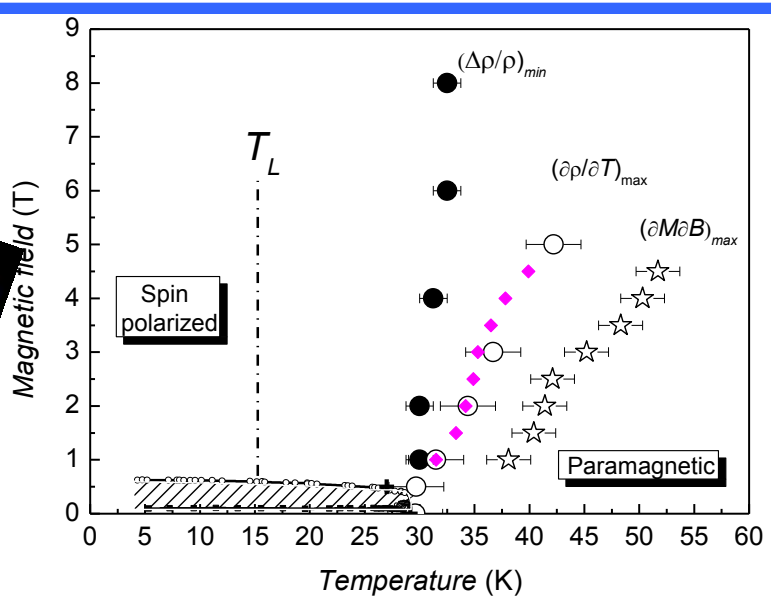
$$R \sim \left(\sum W_{\pm}^{-1}\right)^{-1} \sim \frac{W_0}{2} - \frac{w^2}{2W_0} M^2$$

Due to exchange interaction electrons with spin up and spin down see different scattering potential of magnetic ion

Consequence of the magnetoresistance scaling

$$\frac{\partial\rho(B,T)}{\partial T} = \frac{\partial\rho(0,T)}{\partial T}\{1 - a[M(B,T)]^2\} - 2a\rho(0,T)M(B,T)\frac{\partial M(B,T)}{\partial T}$$

Extrapolation of the ∂ρ/∂T in magnetic field with the help of magnetization data



$$M = M_\infty \tanh[\mu^* B / k_B(T - T_c)]$$

The model

$$B_{\max} = z^*(T)k_B(T - T_c)/\mu^*(T)$$

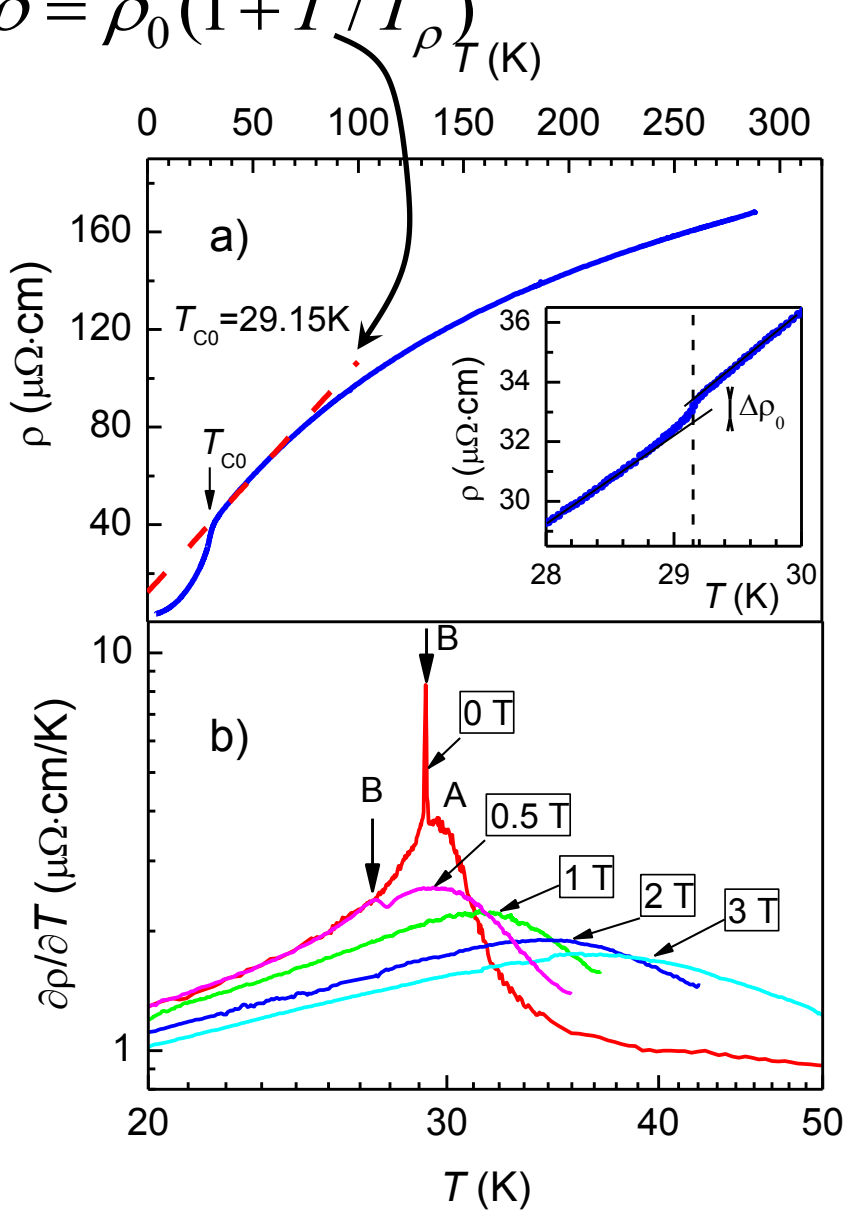
$$(\partial M/\partial B)_{\max} \Rightarrow z\tanh(z) = 1/2 \Rightarrow z^* = 0.772$$

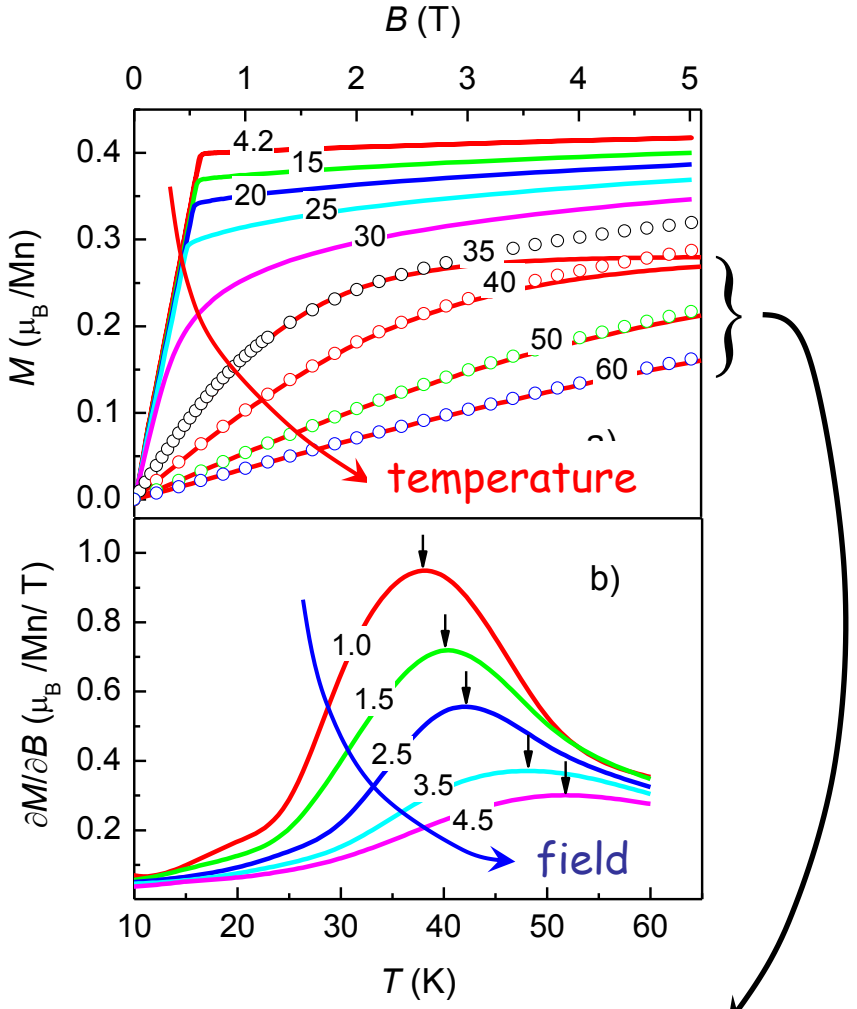
$$(\partial\rho/\partial T)_{\max} \Rightarrow \varphi(T) + z\left[\frac{1}{\tanh z \cosh^2 z} - 2\tanh z\right] = 0$$

$$\varphi(T) = 2[(T_\mu + T)/(T_\rho + T)][(T_\rho + T_c)/(T_\mu + T_c)]$$

$$\mu^* = \mu_0(1 + T/T_\mu); \rho = \rho_0(1 + T/T_\rho)$$

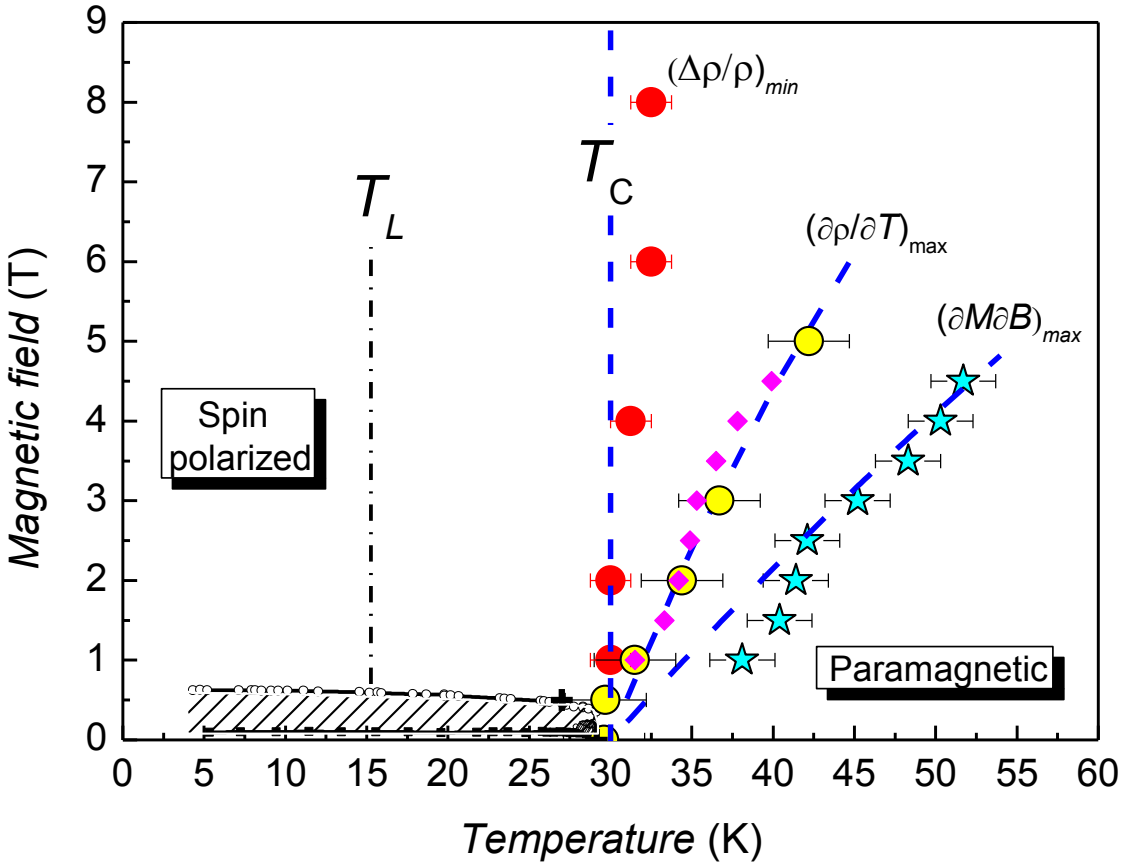
$$\rho = \rho_0 (1 + T/T_\rho)$$



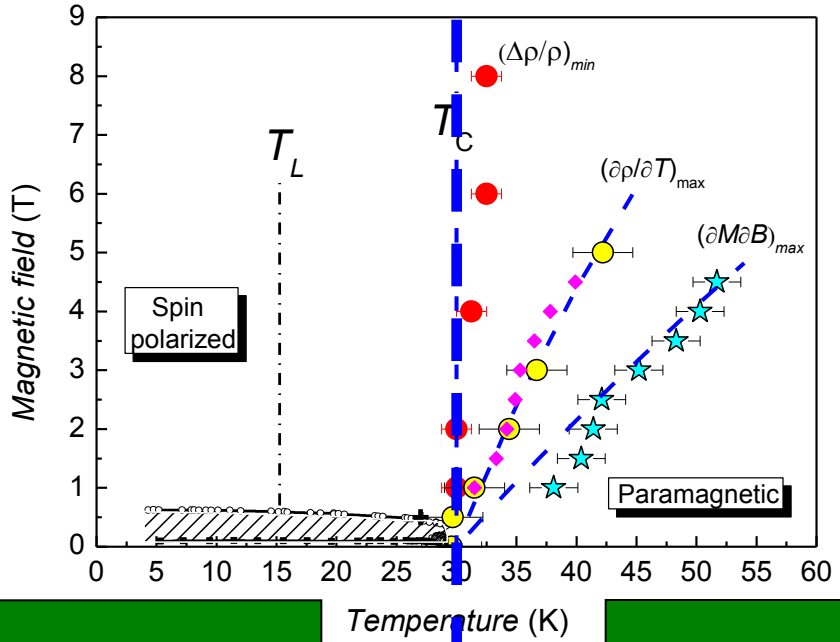


$$M = M_\infty \tanh[\mu^* B / k_B (T - T_c)]$$

$$\mu^* = \mu_0 (1 + T/T_\mu)$$

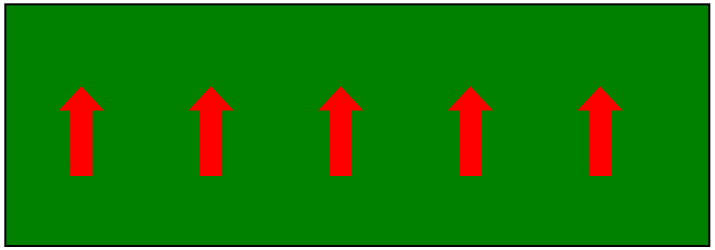


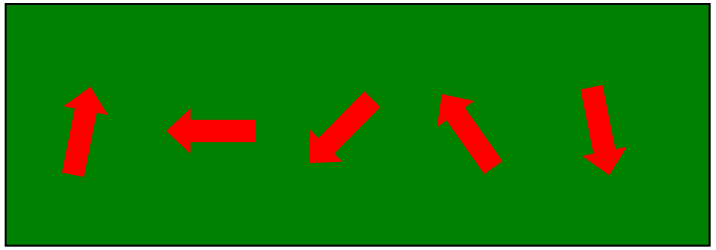
SP-P transition is
sharp,
corresponds to magnetoresistance minimum,
located at Tc~30-31 K.
SP-P boundary is almost vertical. No positive slope.



SP-phase

P-phase





$$\mu(0) = \mu_{LMM} - \mu_B \frac{n_e}{n_{Mn}}$$

$$\frac{n_e}{n_{Mn}} = 0.89$$

$$\mu(0) = (1.29 - 0.89)\mu_B = 0.4\mu_B$$

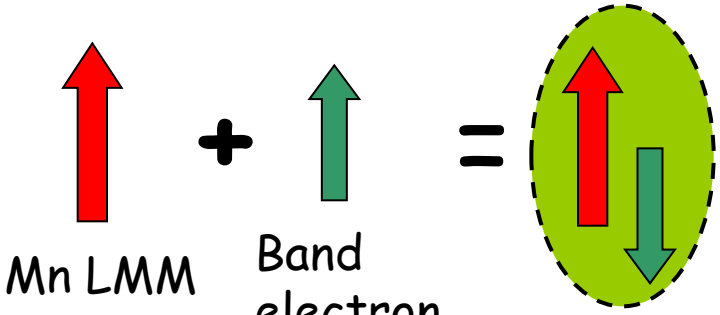
$$\chi = \chi_{LMM} + \chi_{Pauli}$$

$$\chi_{LMM} >> \chi_{Pauli}$$

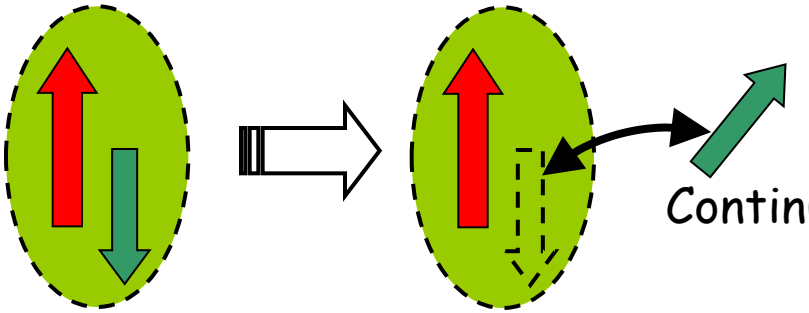
$$\chi = \frac{C}{T - T_c}; Ck_B = 1.66\mu_B{}^2 / Mn$$

$$\mu_{LMM} = 1.29\mu_B$$

Agrees with the LDA value



Spin polaron elementary math



Spin fluctuations are due to transitions between bound and continuum states.

These transitions will destroy possible scattering coherence on neighboring Mn sites in the unit cell and therefore Yosida mechanism of magnetic scattering may work

These transitions will define coherence time for existence of the magnetic state (elementary ferrimagnet) seen by ESR and hence the ESR line width.

g-factor in a ferrimagnet

$$g = g_{Mn} \cdot \frac{1 - y(g_e/g_{Mn})}{1 - y}$$

$$y = [\mu_{Mn} - \mu(0)]/\mu_{Mn}$$

If $g_{Mn} \approx g_e \approx 2$ (the orbital moment is frozen) the g-factor will not change at SP-P phase boundary as observed in ESR experiment.

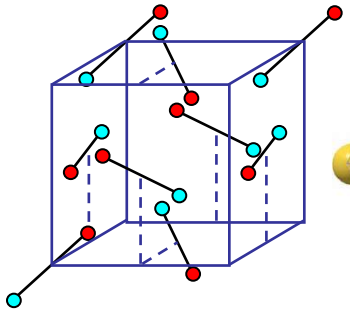
R. K. Wangsness, Phys. Rev. **91**, 1085 (1953)

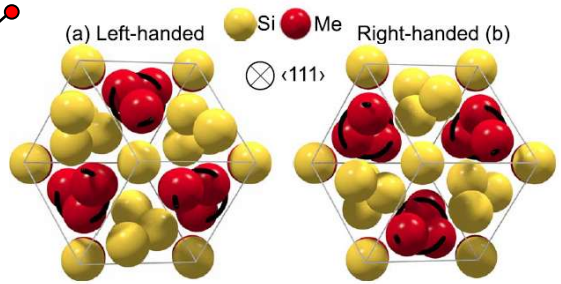
Quantum critical phenomena and ESR

Во всех частях земного шара имеются свои, даже иногда очень любопытные, другие части.

Весьма остроумно замечает Фейербах, что взоры беспутного сапожника следят за штопором, а не за шилом, отчего и происходят мозоли.
К.Прутков

Quantum criticality in $Mn_{1-x}Fe_xSi$. Theoretical expectations.





a=0.456 nm

Mn, Fe
Si

B 20 structure

$Mn_{1-x}Fe_xSi$ substitutional solid solutions (x<0.3).

After decay of the phase with long-range magnetic order an intermediate phase with short-range (fluctuation-driven) magnetic order should be formed. There is underlying QCP.

Intermediate phase may mask quantum critical anomalies like divergent magnetic susceptibility.

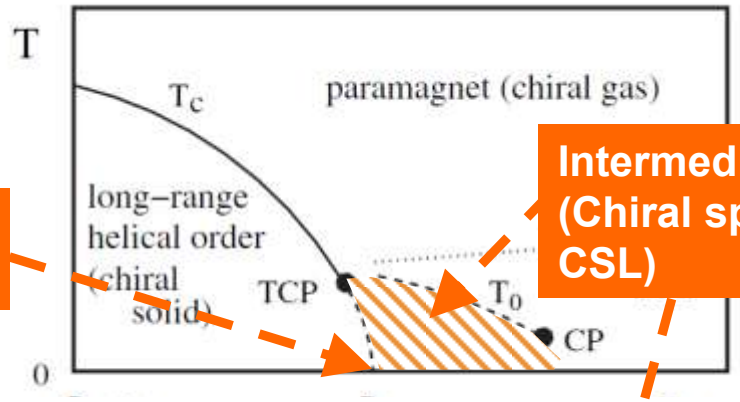
Underlying QCP

Intermediate phase (Chiral spin liquid, CSL)

PHYSICAL REVIEW LETTERS 96, 047207 (2006) week ending 3 FEBRUARY 2006

Blue Quantum Fog: Chiral Condensation in Quantum Helimagnets

Sumanta Tewari,[1,2] D. Belitz,[1,3] and T. R. Kirkpatrick[1,2]

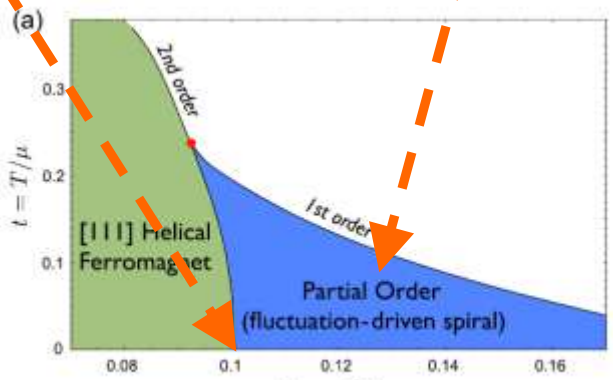


Parameter controlling quantum criticality (pressure, concentration, etc.)

PRL 108, 067003 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

Quantum Order-by-Disorder Near Criticality and the Secret of Partial Order in MnSi

Frank Krüger,[1] Una Karahasanovic,[1] and Andrew G. Green[2]

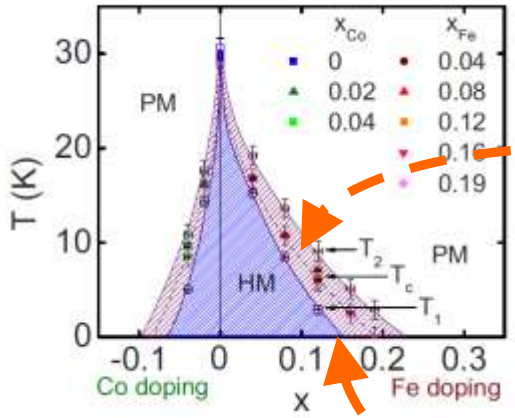


Parameter controlling quantum criticality (pressure, concentration, etc.)

PHYSICAL REVIEW B 82, 064404 (2010)

Quantum phase transitions in single-crystal $Mn_{1-x}Fe_xSi$ and $Mn_{1-x}Co_xSi$: Crystal growth, magnetization, ac susceptibility, and specific heat

A. Bauer,[1] A. Neubauer,[1] C. Franz,[1] W. Münzer,[1] M. Garst,[2,3] and C. Pfleiderer[1,*]



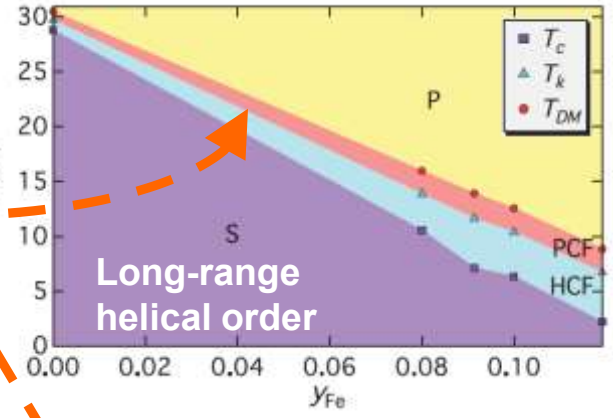
Intermediate phase (Chiral spin liquid, CSL)

Underlying QCP

PHYSICAL REVIEW B 83, 224411 (2011)

Chiral criticality in the doped helimagnets $Mn_{1-y}Fe_ySi$

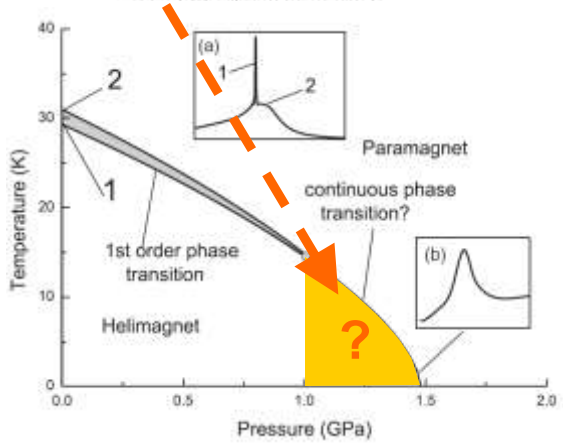
Sergey V. Grigoriev,[1] Evgeny V. Moskvin,[1] Vadim A. Dyadkin,[1] Daniel Lamago,[2,3] Thomas Wolf,[3] Helmut Eckerlebe,[4] and Sergey V. Maleyev[1]



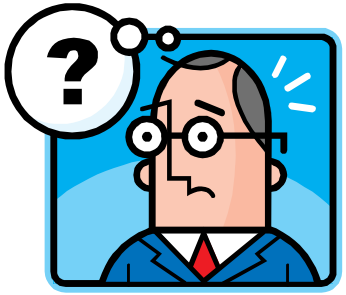
PHYSICAL REVIEW B 86, 174407 (2012)

Phase diagram of the itinerant helimagnet MnSi from high-pressure resistivity measurements and the quantum criticality problem

Alla E. Petrova and Sergei M. Stishov



Experimental magnetic phase diagrams differ from the theoretical ones.



What kind of QC points we have?

Is there any true QC anomalies?

How T-x phase diagram is constructed?

PHYSICAL REVIEW B 83, 224411 (2011)

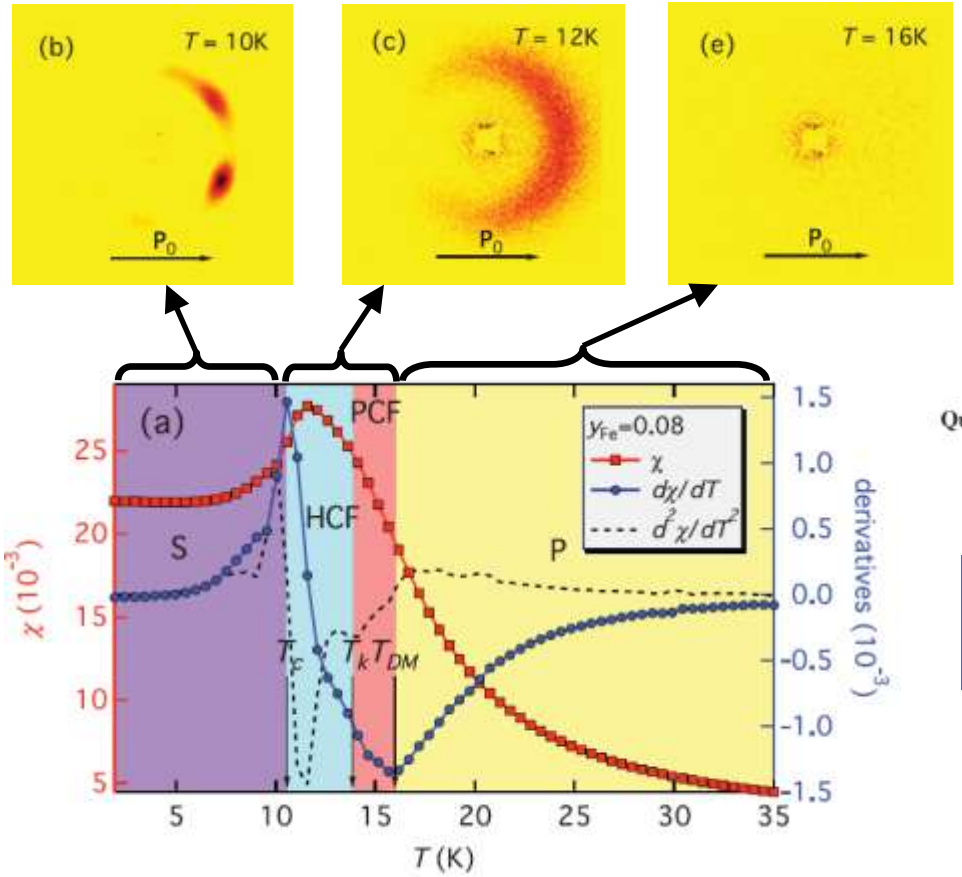
Chiral criticality in the doped helimagnets $Mn_{1-y}Fe_ySi$

Sergey V. Grigoriev,[1] Evgeny V. Moskvin,[1] Vadim A. Dyadkin,[1] Daniel Lamago,[2,3] Thomas Wolf,[3] Helmut Eckerlebe,[4] and Sergey V. Maleyev[1]

Long-range magnetic order (Chiral solid)

Short-range magnetic order (Chiral liquid)

Paramagnet (Chiral gas)



Correlation between magnetic susceptibility and polarized neutron scattering data is established in $Mn_{1-x}Fe_xSi$.

The extrema of the $\partial\chi/\partial T$ derivative may be used for identification of the magnetic phases with long-range and short-range magnetic order.

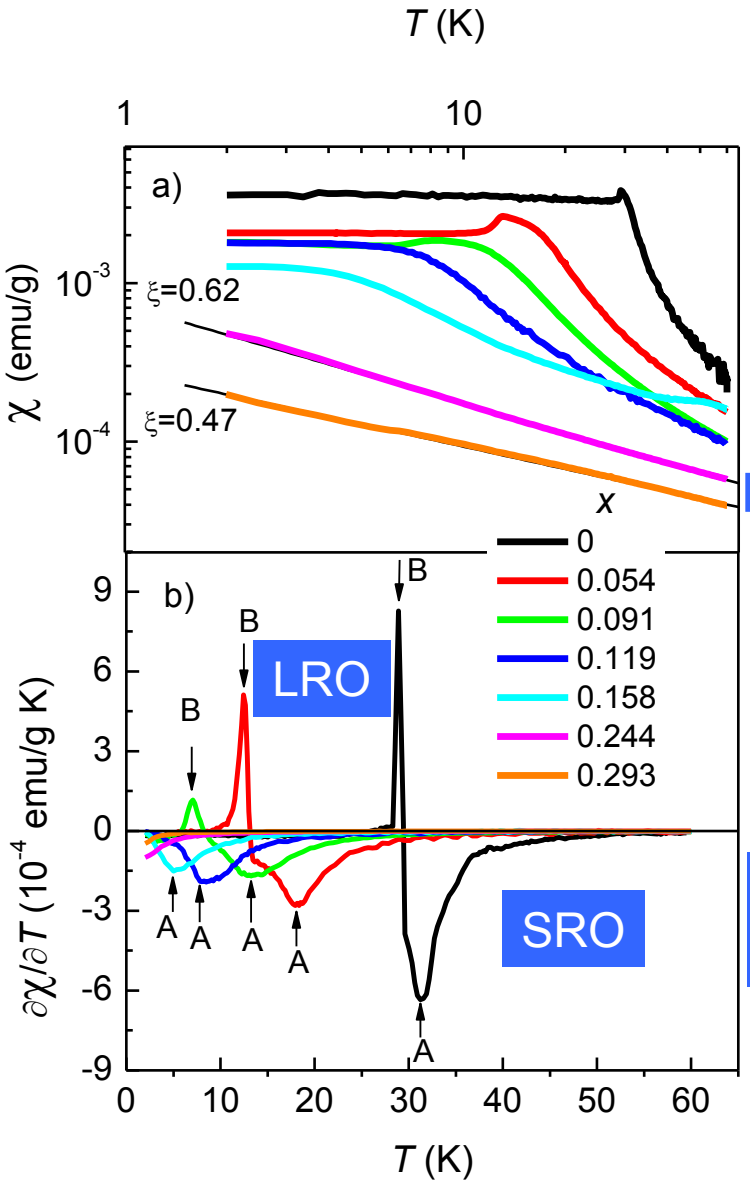
PHYSICAL REVIEW B 82, 064404 (2010)

Quantum phase transitions in single-crystal $Mn_{1-x}Fe_xSi$ and $Mn_{1-x}Co_xSi$: Crystal growth, magnetization, ac susceptibility, and specific heat

A. Bauer,[1] A. Neubauer,[1] C. Franz,[1] W. Münzer,[1] M. Garst,[2,3] and C. Pfleiderer[1,*]

Classical ferromagnetic equation of state is applicable for $Mn_{1-x}Fe_xSi$.

Belov-Arrott analysis is possible

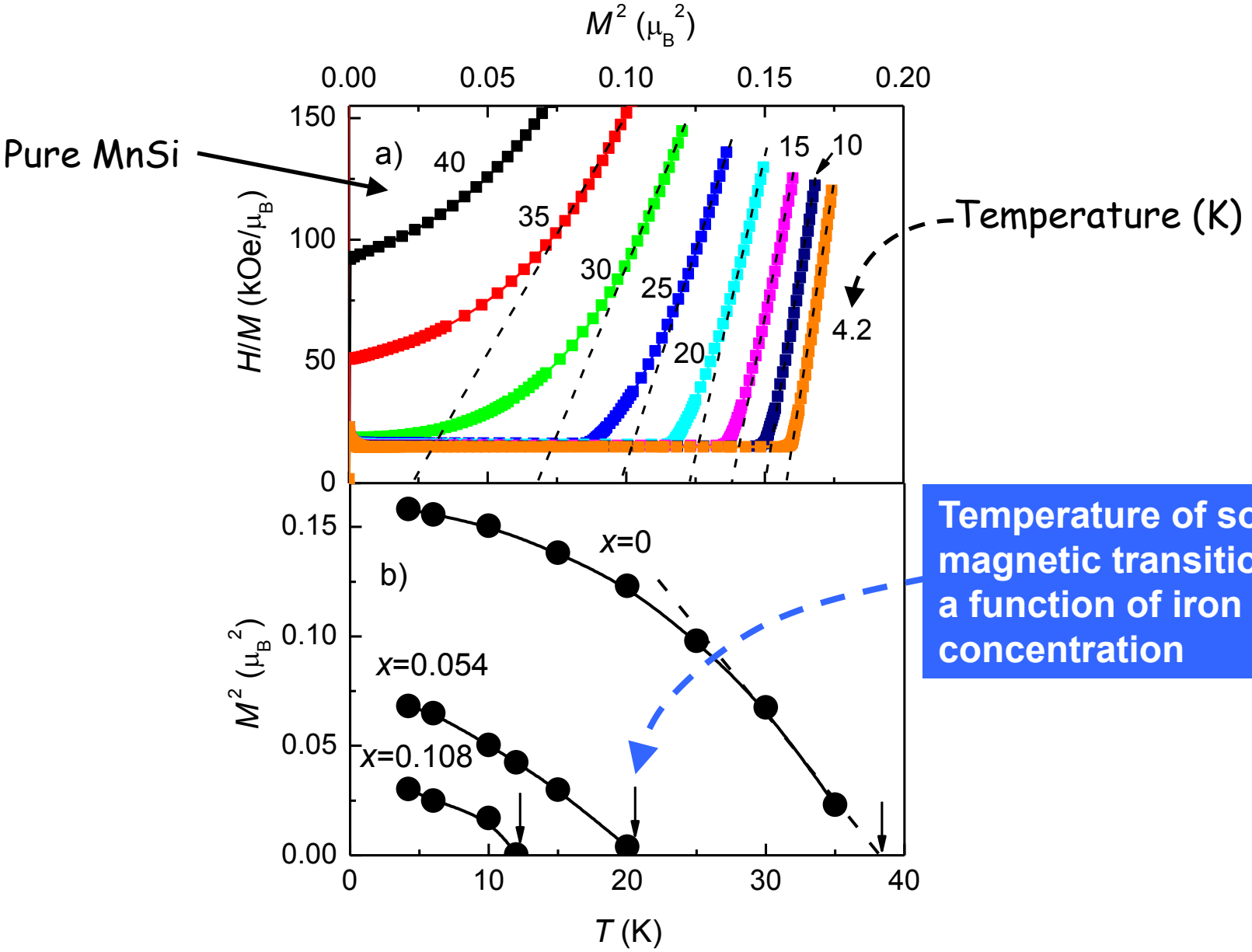


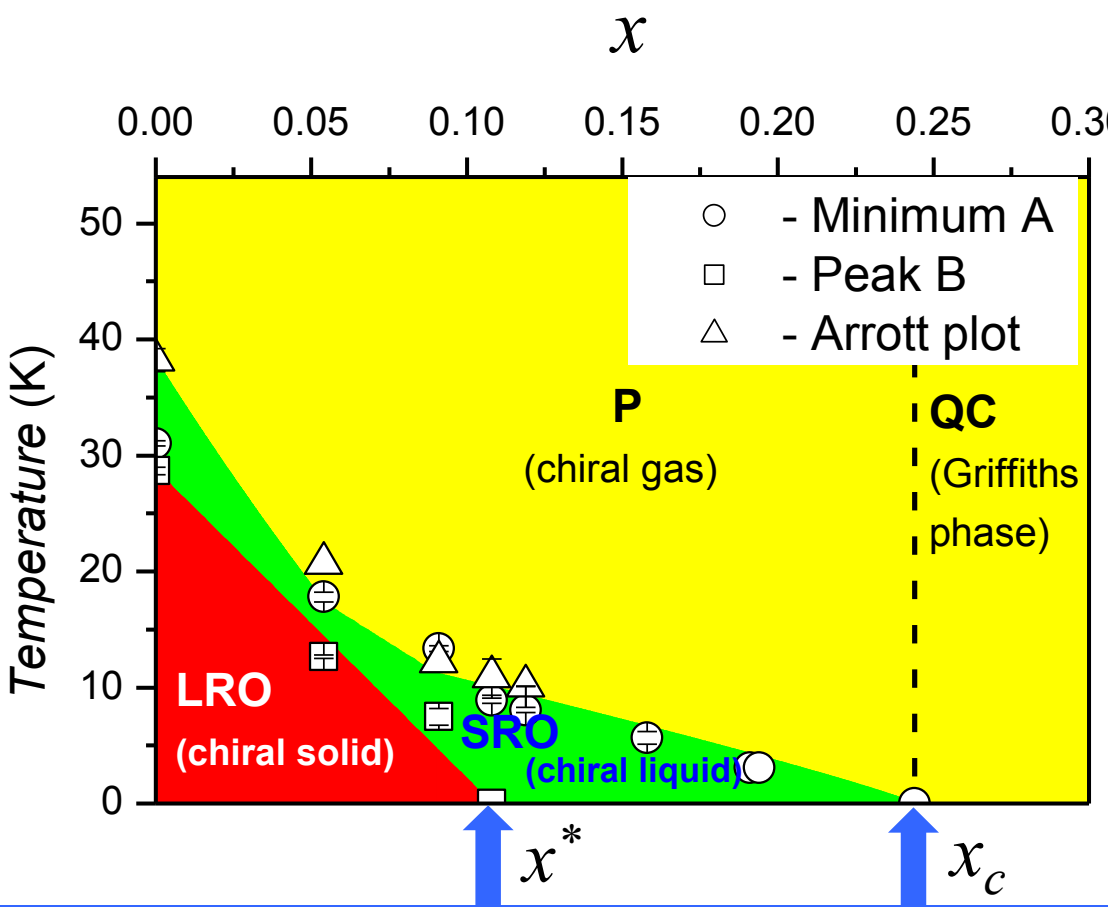
Griffiths-type QC anomaly for $x > 0.24$

$$\chi \sim \frac{1}{T^{\xi}} \qquad \xi \sim 0.5 - 0.6$$

Peak B is a marker of long-range magnetic order (LRO).

Minimum A is a marker of short-range magnetic order (SRO).


Pure MnSi
M^2 (μ_B^2)
0.00
0.05
0.10
0.15
0.20
a)
40
35
30
25
20
15
10
4.2
Temperature (K)
H/M (kOe/μ_B)
150
100
50
0
b)
x=0
x=0.054
x=0.108
M^2 (μ_B^2)
0.15
0.10
0.05
0.00
0
10
20
30
40
T (K)
Temperature of some magnetic transition as a function of iron concentration



Both susceptibility and Arrott analysis give characteristic temperatures above transition into the magnetic phase with spiral LRO. These temperatures corresponds to formation of the magnetic phase with SRO (chiral spin liquid).

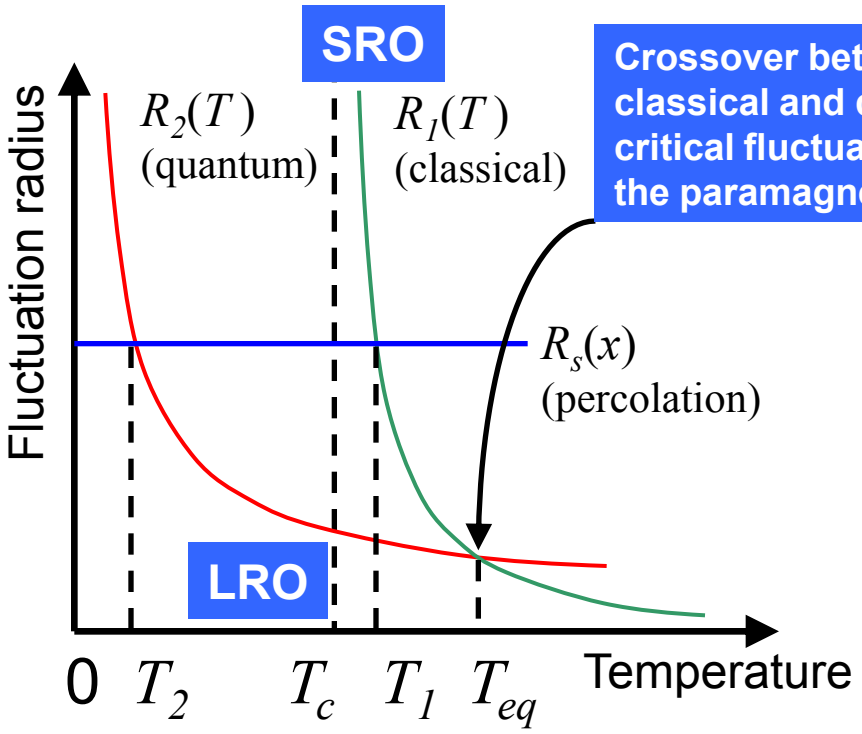
There are two quantum critical points, x^* and x_c. The first QC point x^* ~ 0.11 corresponds to disappearance of LRO and is an underlying one, which is hidden inside the SRO phase. The second QC point x_c ~0.24 is a "true" one and marks suppression of the magnetic phase with SRO (chiral spin liquid).

Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions.

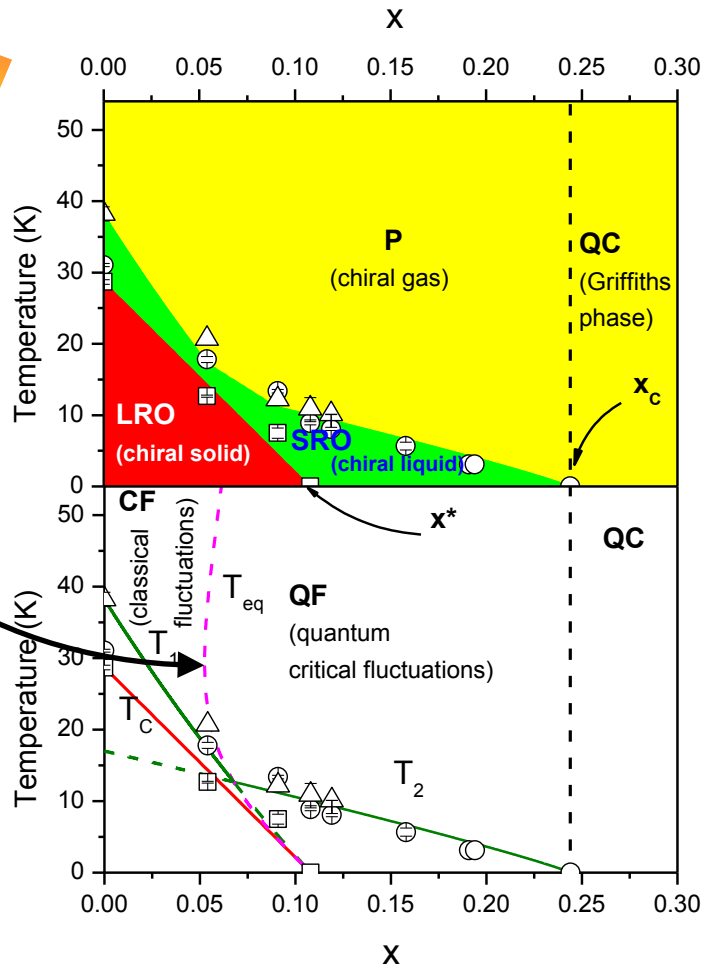
Pis'ma v ZhETF, vol. 98, iss. 12, pp. 933 – 937 © 2013 December 25

Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions: exchange and percolation effects

S. V. Demishev+[1], I. I. Lobanova++, V. V. Glushkov++, T. V. Ischenko+, N. E. Sluchanko+, V. A. Dyadkin, N. M. Potapova, S. V. Grigoriev



Crossover between classical and quantum critical fluctuations in the paramagnetic phase



Presence of both classical and quantum critical fluctuations.

Phase with short-range order is formed when fluctuations slow down and freeze.

Fluctuations freeze when their radius reaches critical value controlled by disorder (or defects) in the system.

Classical fluctuations (CF): $R_1 = \dfrac{a_1}{[T/T_c(x)-1]^{\delta}}$; $\delta \sim 1/2$

Quantum critical fluctuations (QF): $R_2 = a_2 \dfrac{T_0}{T}$

Defects and disorder (percolation):

$R_s = R_c = \dfrac{l}{(1-x/x_c)^{\nu}}$; $\nu \sim 0.9$, x_c - percolation threshold

$R_{1,2} = R_s \Rightarrow T_{1,2}(x)$ Freezing condition

$R_1 = R_2 \Rightarrow T_{eq}(x)$ Crossover between CF and QF

There is only one fitting parameter $T_2(0)$ (measure of the quantum critical fluctuations strength).

Transition into LRO phase

$T_c(x) = T_c(0)(1-x/x^*)$

Transition into SRO phase:

$T(x) = \max\{T_1(x), T_2(x)\}$

$$T_1 = T_c(x)\left\{1 + \frac{\delta T(0)}{T_c(0)}\left(1 - \frac{x}{x_c}\right)^{\nu/\delta}\right\}$$

$$T_2 = T_2(0)\left(1 - \frac{x}{x_c}\right)^{\nu}$$

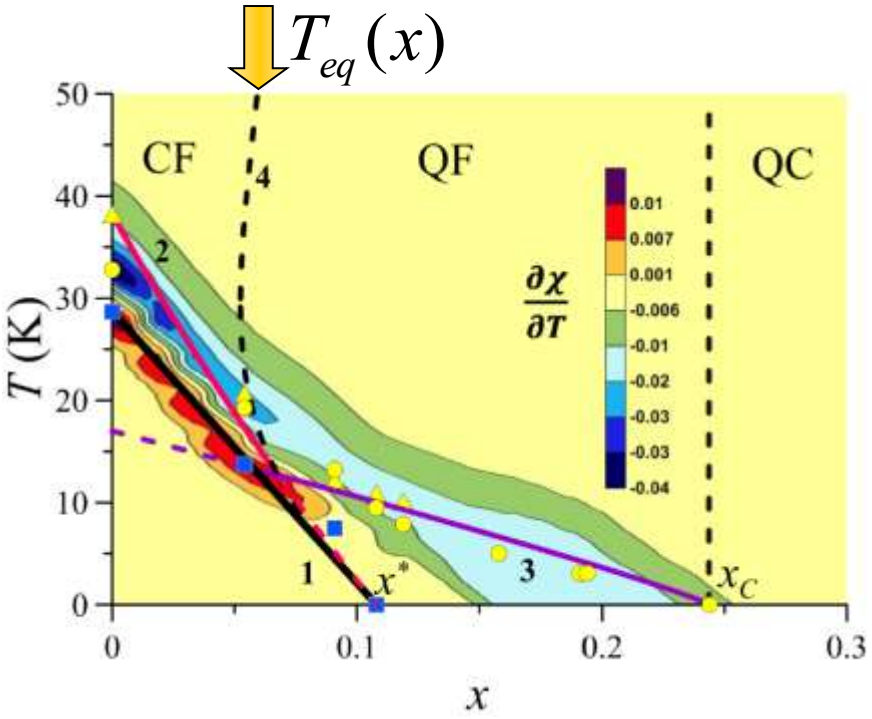
$$\delta T(0) = T_c(0)\left(\frac{a_1}{l}\right)^{1/\delta};\ T_2(0) = T_0\frac{a_2}{l}$$

CF - QF crossover temperature for model choice $\delta = 1/2$

$$A = \frac{z^2}{z-1} \Rightarrow T_{eq}(x)$$

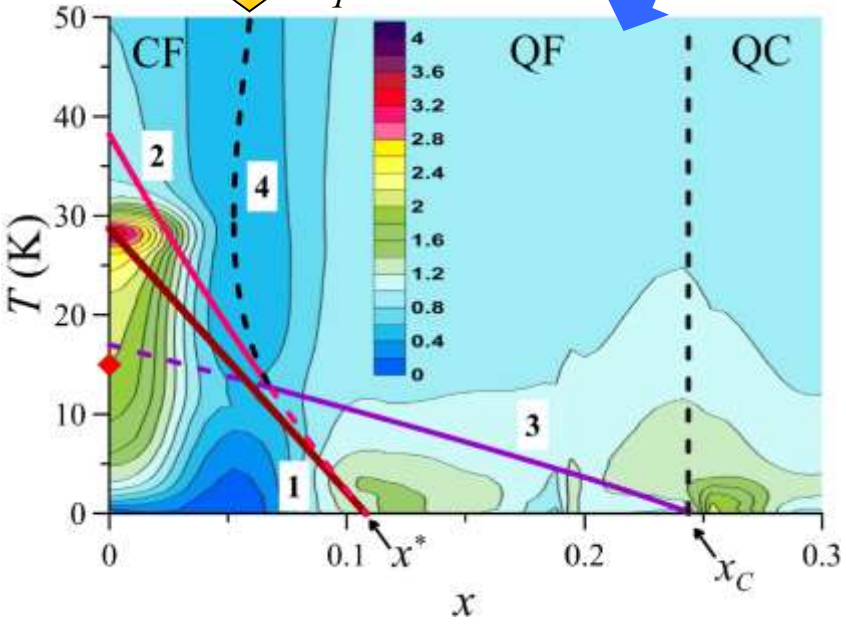
$$z = \frac{T_{eq}}{T_c(x)};\quad A = \frac{T_2(0)^2 T_c(0)}{\Delta T(0) T_c(x)^2}$$

No $T_{eq}(x)$ in the $\partial\chi/\partial T$ data!



Analysis of the resistivity data:

$$\rho(T) = \rho_0 + A \cdot T^{\alpha} \Rightarrow \alpha(x,T)$$



The predicted crossover line is observed in the resistivity data due to scattering on magnetic fluctuations (Yosida mechanism).

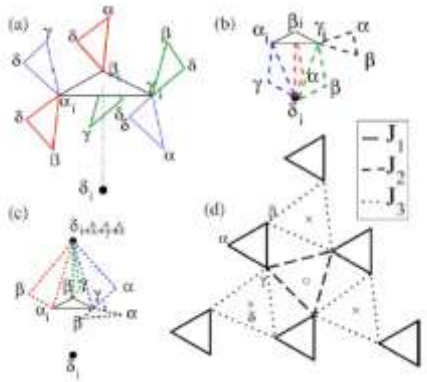
In the case of static susceptibility these fluctuations are averaged and don't affect $\chi(T)$ data.

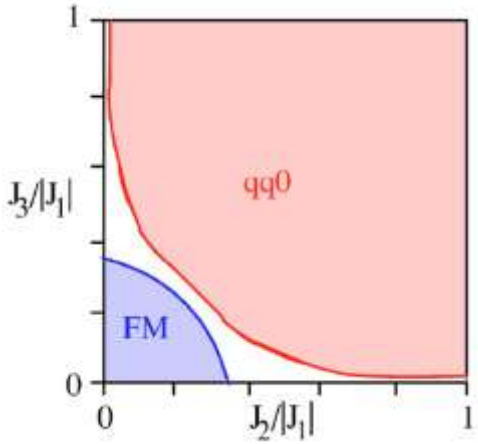
Why intermediate phase is formed? Why LRO phase is supressed?

PHYSICAL REVIEW B 75, 064430 (2007)

Microscopic model for spiral ordering along (110) on the MnSi lattice

John M. Hopkinson* and Hae-Young Kee†





J_1 – nn (FM) exchange

J_2 – next nn (AFM) exchange

J_3 – third nn (AFM) exchange

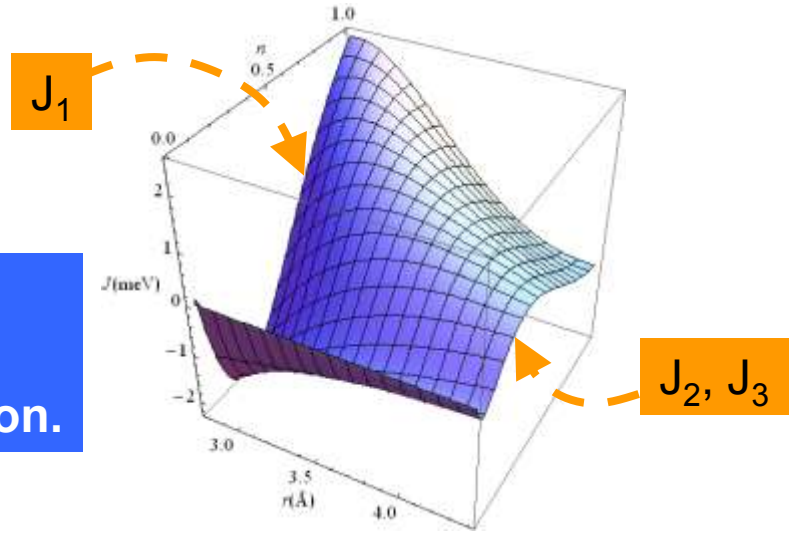
$J_2 \cong J_3$

$|J_2 / J_1|_{cr} \sim 0.21 - 0.32$

Frustration try to align spirals along (110).

DM interaction try to align spirals along (111)

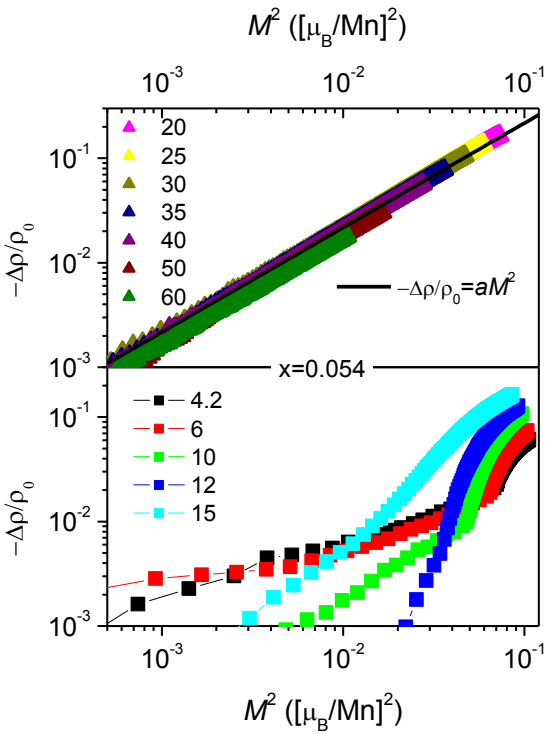
Competition between two interactions may lead to loosing of the long-range order and formation of the chiral liquid state.

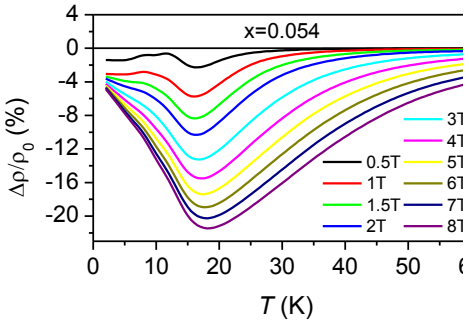


In Heisenberg paradigm RKKY exchange defines J_1, J_2, J_3 parameters, which may be tuned by variation of the electron concentration.

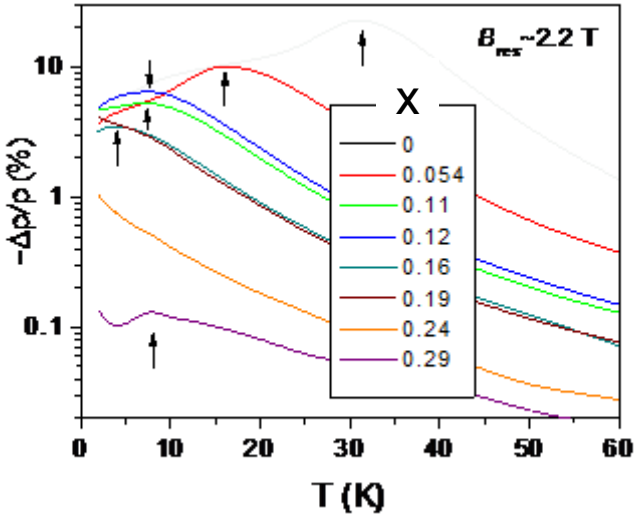
QC points and ESR. Phase diagram of $Mn_{1-x}Fe_xSi$ for $B=B_{res}$.

Yosida mechanism holds in $Mn_{1-x}Fe_xSi$.

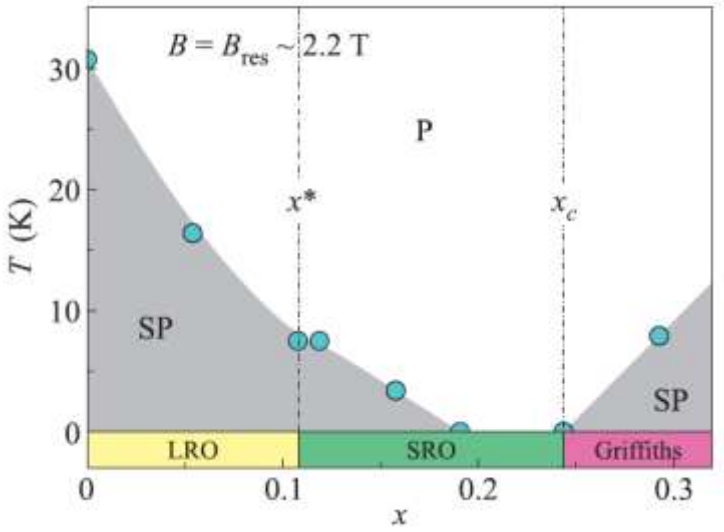




Magnetoresistance maximum evolution with iron concentration.



Phase diagram in magnetic field corresponding to magnetic resonance

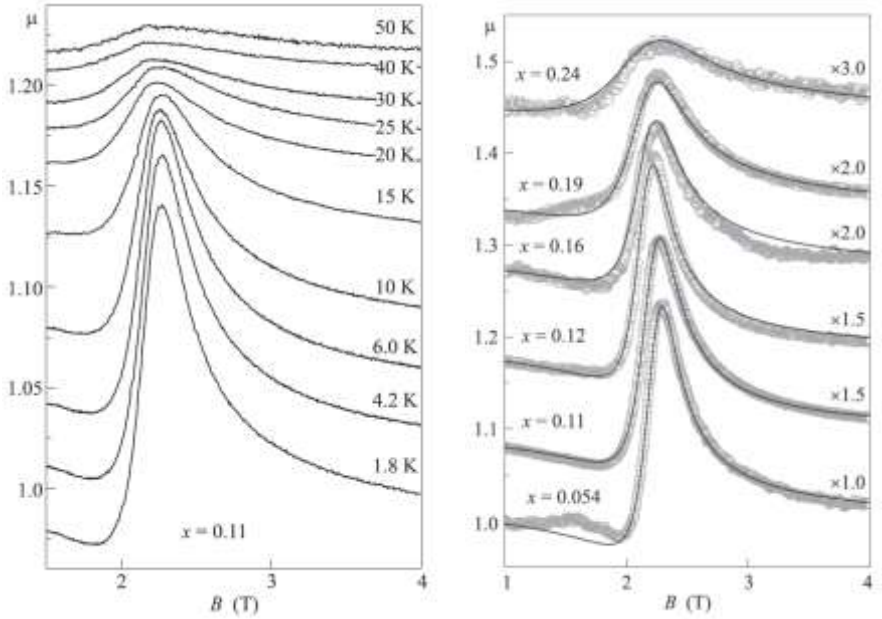


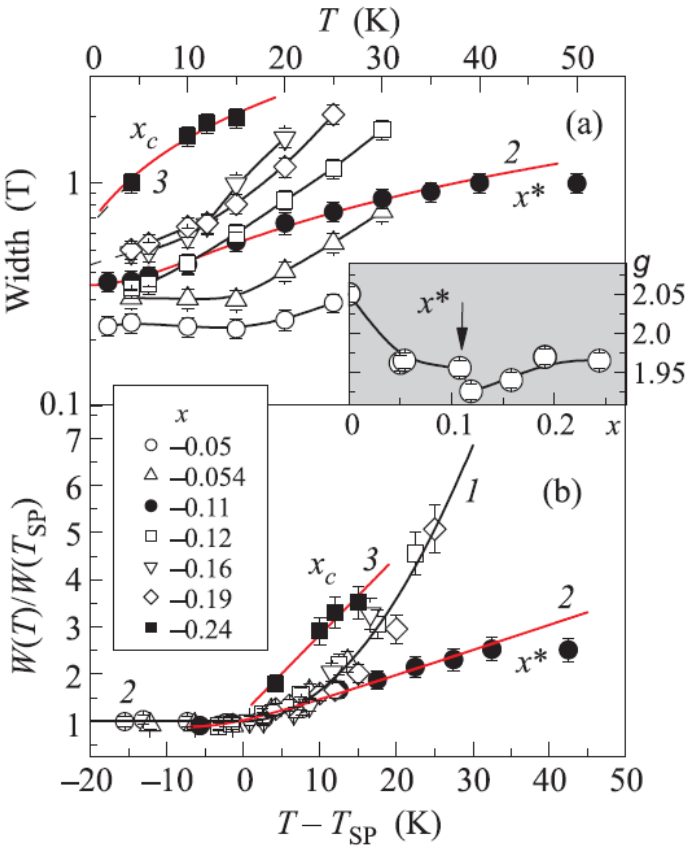
Pis'ma v ZhETF, vol. 100, iss. 1, pp. 30 - 33
© 2014 July 10

Anomalous spin relaxation and quantum criticality in $Mn_{1-x}Fe_xSi$ solid solutions[1)]

S. V. Demishev[+*2)], A. N. Samarin[+*], V. V. Glushkov[+*], M. I. Gilmanov[+*], I. I. Lobanova[+*], N. A. Samarin[+], A. V. Semeno[+], N. E. Sluchanko[+], N. M. Chubova[×], V. A. Dyadkin[×], S. V. Grigoriev[×]

60 GHz ESR spectra





Strong broadening of the line width (enhancement of spin fluctuations) with iron concentration.

Universal scaling $W(T)/W(T_{SP})=1+a(T-T_{SP})^2$ for all concentrations except quantum critical points x* and x_c.

Violation of the standard Korringa relaxation law $W(T)\sim 1/\chi(T)\sim(T-T_{SP})$.

Weakening of the $W(T)$ temperature dependence just at quantum critical points.

ESR in $Mn_{1-x}Fe_xSi$. Theory vs. experiment.

Theory of the ESR in strongly correlated metals

Korringa relaxation should be valid eve… strongly correlated metallic case

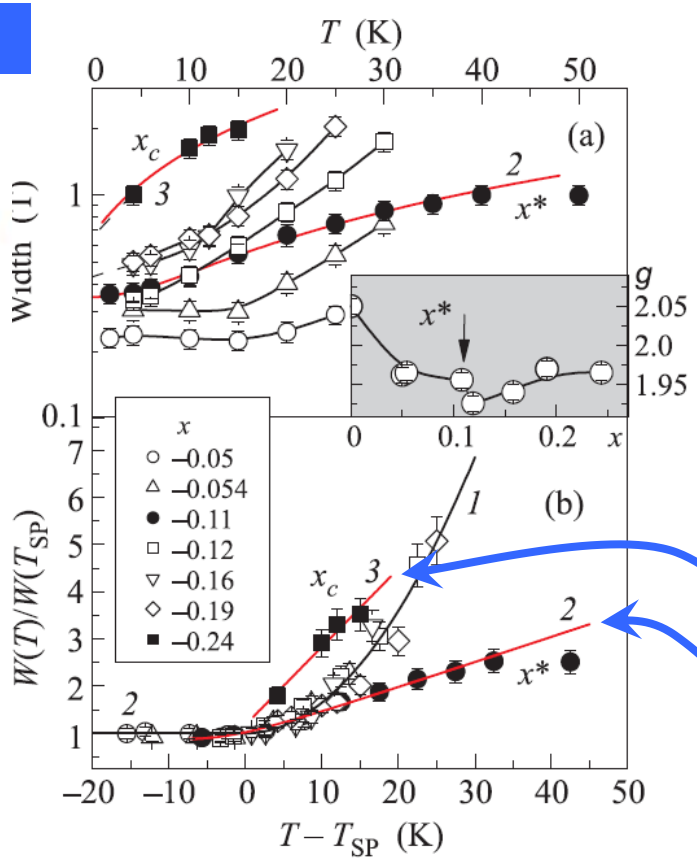
P. Schlottmann, Phys. Rev. B **86**, 075135 (2012

Expression for ESR line width in strongly correlated metal in vicinity of the QC point:

$$W(T) = AT \arctan(T/T_x) + W_0$$

T_x is a crossover temperature between Fermi-liquid $(T \ll T_x)$ and non-Fermi-liquid $(T \gg T_x)$ regimes.

P. Wölfle and E. Abrahams, Phys. Rev. B **80**, 235112 (2009).



Reasonable fit of the experimental data assuming $T_x \sim T_{SP}$, i.e. $T_x \sim 11$ K for x^* and $T_x \sim 0$K for x_c.

Even in strong magnetic field QC points x* and x_c derived in the limit B→0 a…

ESR is a right tool to visualize QC points including the underlying QC point.

Conclusions.

Magnetic phase diagram of $Mn_{1-x}Fe_xSi$ is driven by the sequence of two quantum phase transitions.

First (underlying) QCP is located at x^*~0.11 and controlled by exchange effects.

Second QCP is located at x_c~0.24 and is disorder controlled. This QC point corresponds to the change of the magnetic system topology at the percolation threshold. For $x>x_c$ ground state is a Griffiths phase.

New line on T-x diagram, which corresponds to a crossover between the classical and quantum fluctuations, is predicted in quantum bicritical model and observed experimentally.

Substitution of Mn by Fe leads to enhancement of spin fluctuations (a route from Heisenberg to itinerant case).

Anomalous spin relaxation is a tool to visualize QC points in ESR experiments.

MnSi и Mn1-xFexSi как жидкие кристаллы

Т.В. Ищенко

Не совсем понимаю: почему многие называют судьбу индейкою, а не какою-либо другою, более на судьбу похожею птицею?

Не шути с женщинами: эти шутки глупы и неприличны.
К.Прутков

Аналогия между жидкими кристаллами и киральными магнетиками. 1

PRL 96, 047207 (2006) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2006

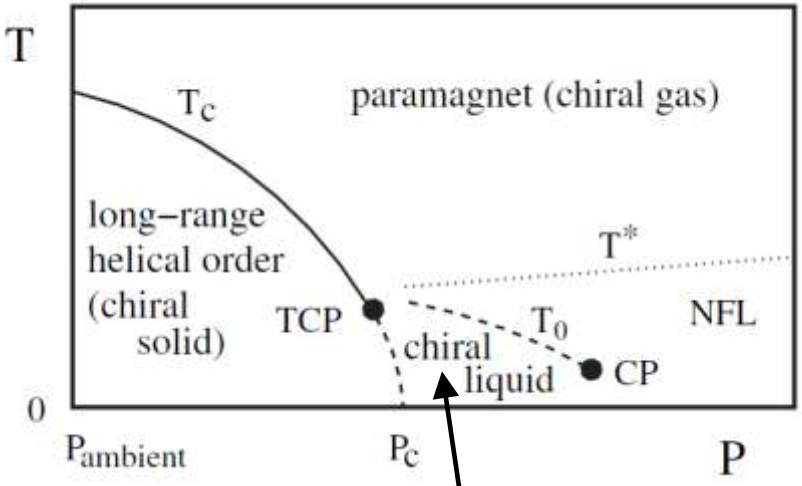
Blue Quantum Fog: Chiral Condensation in Quantum Helimagnets

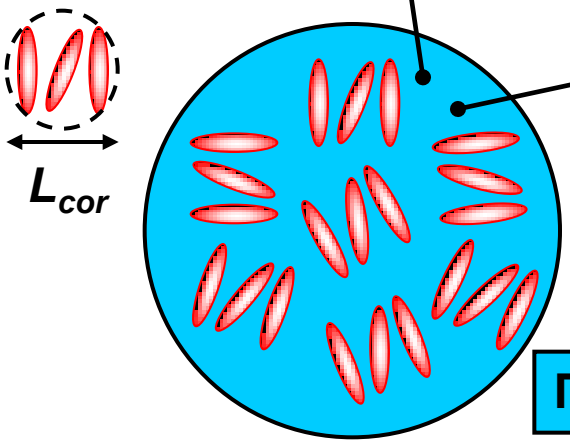
Sumanta Tewari,[1,2] D. Belitz,[1,3] and T. R. Kirkpatrick[1,2]

Pis'ma v ZhETF, vol. 98, iss. 12, pp. 933 - 937 © 2013 December 25

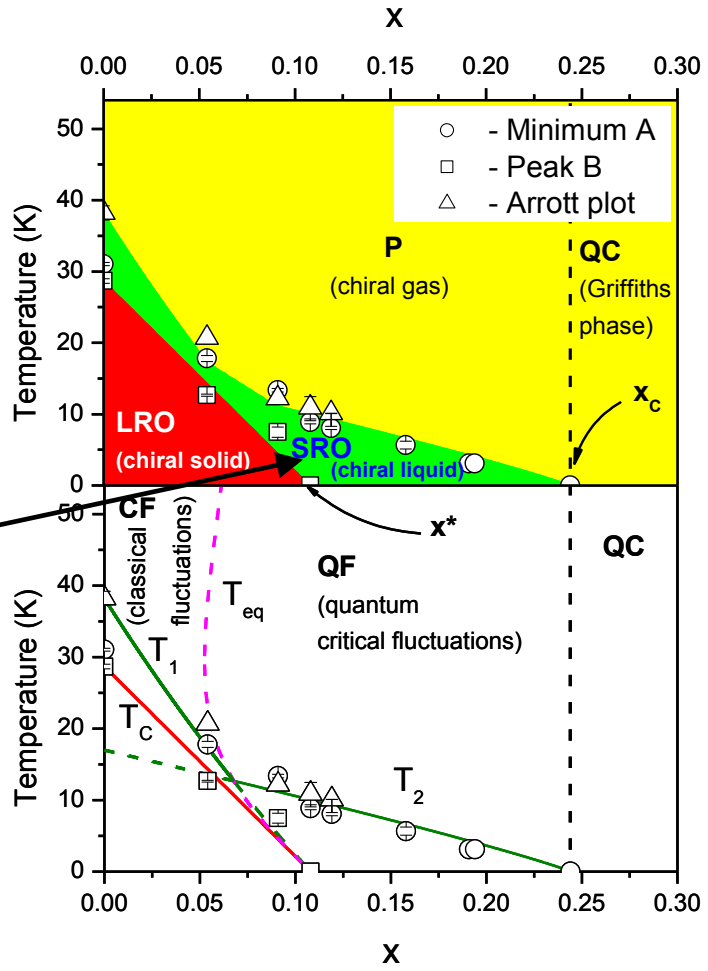
Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions: exchange and percolation effects

S. V. Demishev+[1], I. I. Lobanova++, V. V. Glushkov++, T. V. Ischenko+, N. E. Sluchanko+, V. A. Dyadkin, N. M. Potapova, S. V. Grigoriev





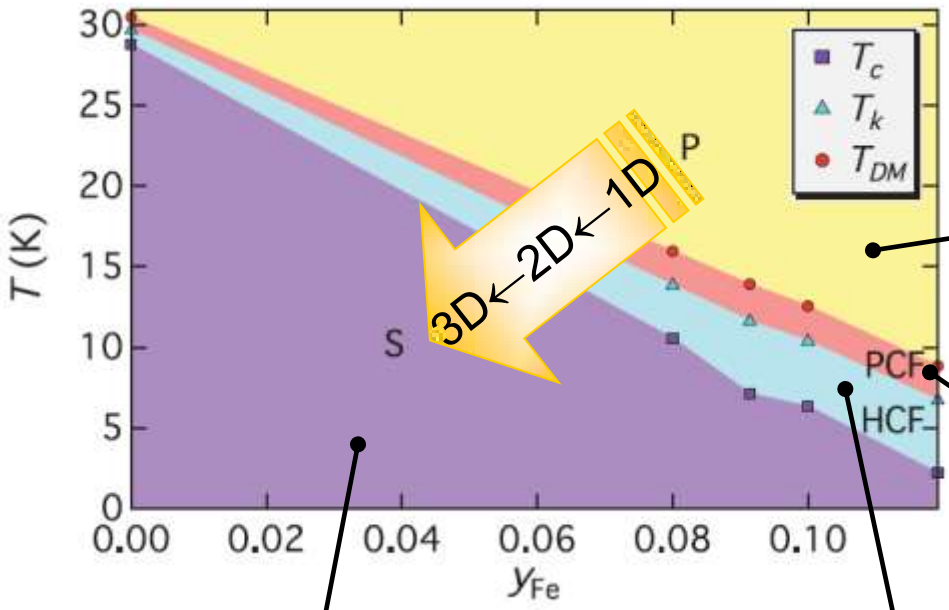
Голубая фаза



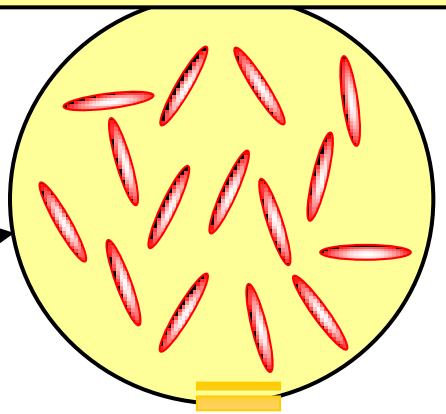
PHYSICAL REVIEW B 83, 224411 (2011)

Chiral criticality in the doped helimagnets $Mn_{1-y}Fe_ySi$

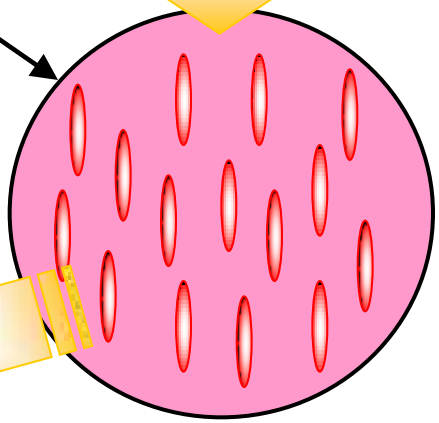
Sergey V. Grigoriev,[1] Evgeny V. Moskvin,[1] Vadim A. Dyadkin,[1] Daniel Lamago,[2,3] Thomas Wolf,[3] Helmut Eckerlebe,[4] and Sergey V. Maleyev[1]



Парамагнитная фаза – «изотропная жидкость»

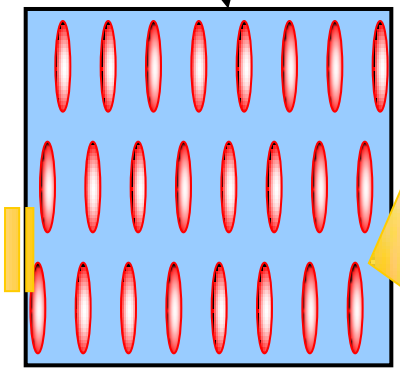


1D



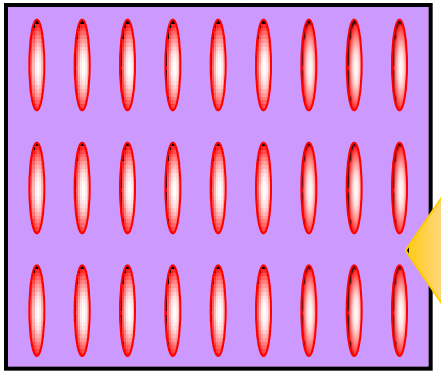
«Нематик»

2D



«Смектик»

3D



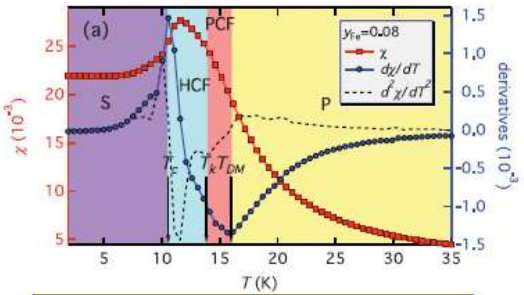
Кристалл

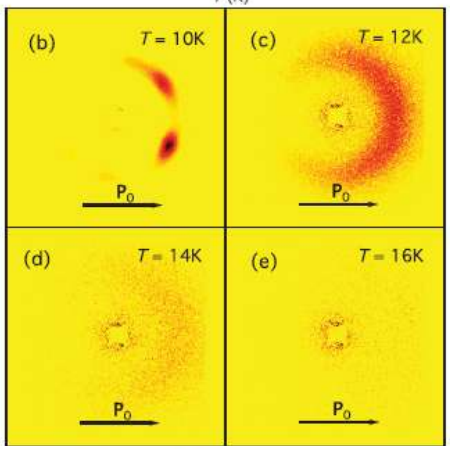
Малоугловое рассеяние нейтронов

PHYSICAL REVIEW B 83, 224411 (2011)

Chiral criticality in the doped helimagnets $Mn_{1-y}Fe_ySi$

Sergey V. Grigoriev,[1] Evgeny V. Moskvin,[1] Vadim A. Dyadkin,[1] Daniel Lamago,[2,3] Thomas Wolf,[3] Helmut Eckerlebe,[4] and Sergey V. Maleyev[1]

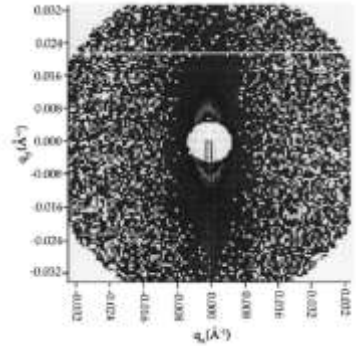




PHYSICAL REVIEW E 68, 011709 (2003)

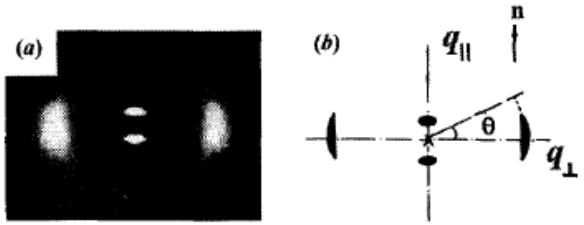
Structure and texture of anisotropic nematic gels

P. Gautier,[1,2,*] M. Brunet,[2] J. Grupp,[1] L. Noirez,[3] and E. Anglaret[2]

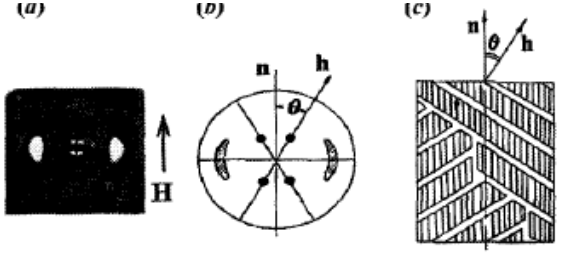


Рентгеноструктурный анализ

Рентгеновские дифрактограммы *п*-анизаламино-коричной кислоты в различных фазах, слева направо: нематик, смектик-А, кристаллический смектик-B_{cr}



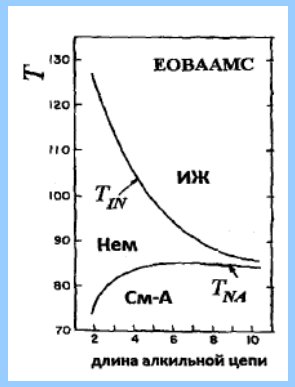
Типичная рентгенограмма нематического жидкого кристалла с директором ориентированным вертикально (*a*) и схема, поясняющая эту дифракционную картину (*b*)

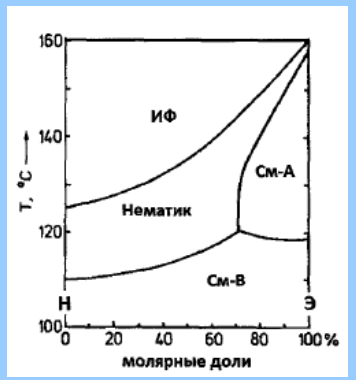


Смектическая С фаза в магнитном поле, ориентированном в вертикальном направлении, **H||n**. Типичная рентгенограмма (*a*) и ее схема (*b*), поясняющие 4-точечную картину расположения отражений от смектических слоев в области малых углов; система слоев с двумя противоположными направлениями наклона (*c*)

Блинов Лев Михайлович
Жидкие кристаллы: Структура и свойства. М.: Книжный дом «ЛИБРОКОМ», 2013.

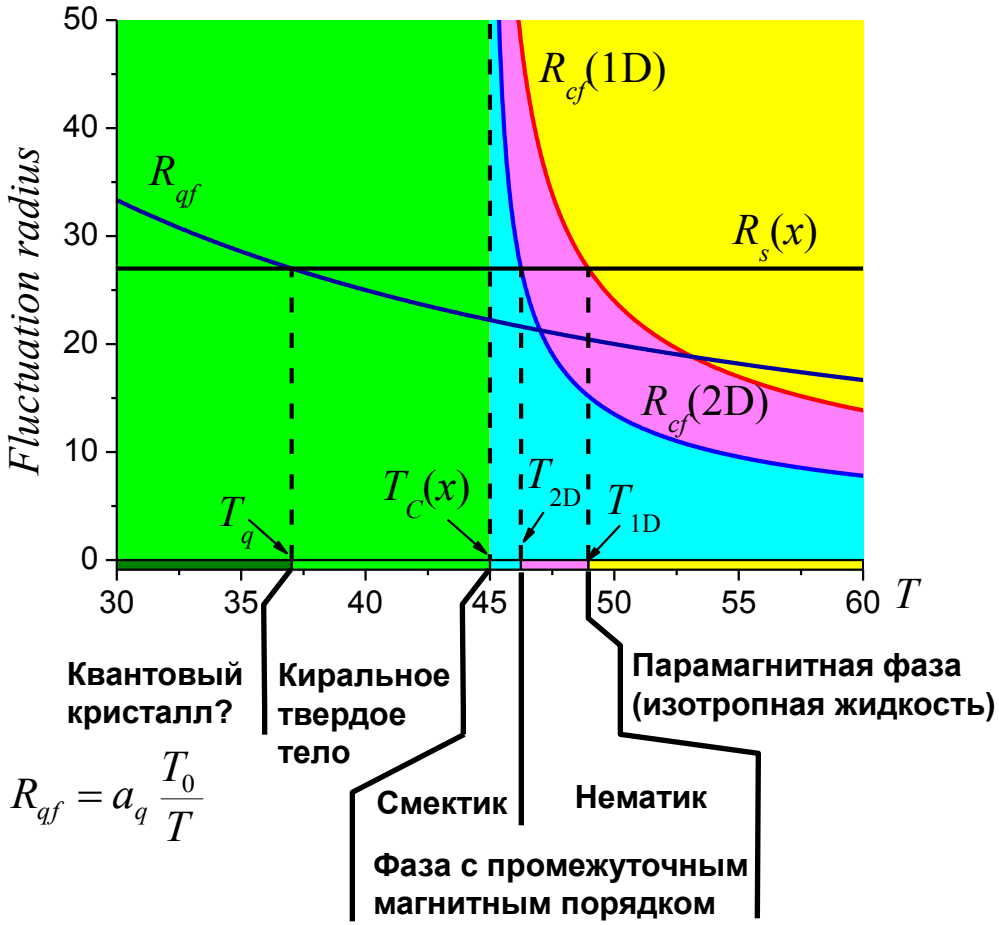
Фазовые диаграммы жидких кристаллов





4-этоксибензол-4'-амино-*n*-алкил-α-метил коричной кислоты

Анизотропная модель



$$R_{cf}(1D) = R_s; \quad R_{cf}(2D) = R_s; \quad R_{qf} = R_s$$

$$R_s = R_c(x) = \frac{l}{(1 - x/x_c)^{\nu}}$$

$$R_{cf}(1D) = \frac{a_{1D}}{(T/T_c - 1)^{\delta}}; \quad R_{cf}(2D) = \frac{a_{2D}}{(T/T_c - 1)^{\delta}}; \quad R_{qf} = a_q \frac{T_0}{T}$$

$$T_{1D,2D}(x) = T_c(x)\left[1 + \frac{\Delta T_{1D,2D}(0)}{T_c(0)}\left(1 - \frac{x}{x_c}\right)^{\nu/\delta}\right]$$

$$T_q(x) = T_q(0)\left(1 - \frac{x}{x_c}\right)^{\nu}$$

Pis'ma v ZhETF, vol. 98, iss. 12, pp. 933 – 937 © 2013 December 25

Quantum bicriticality in $Mn_{1-x}Fe_xSi$ solid solutions: exchange and percolation effects

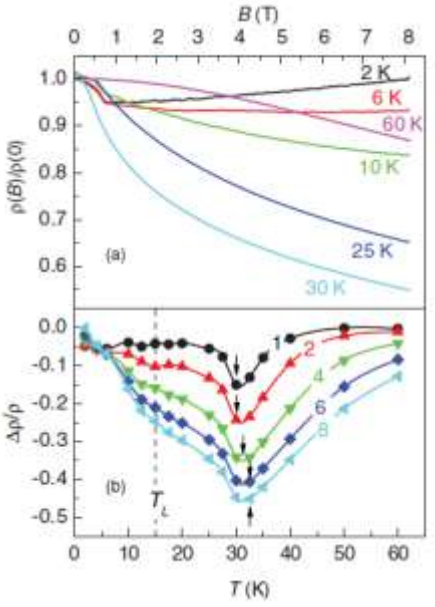
S. V. Demishev+1), I. I. Lobanova++, V. V. Glushkov++, T. V. Ischenko+, N. E. Sluchanko+, V. A. Dyadkin, N. M. Potapova, S. V. Grigoriev

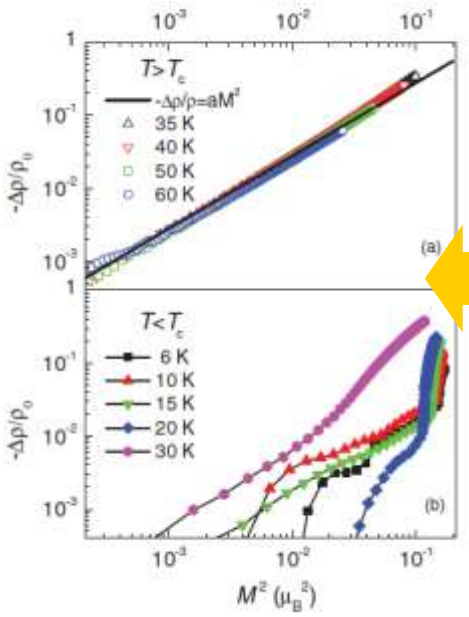
Магнитное поле и «жидкокристаллические» фазы $Mn_{1-x}Fe_xSi$.

PHYSICAL REVIEW B 85, 045131 (2012)

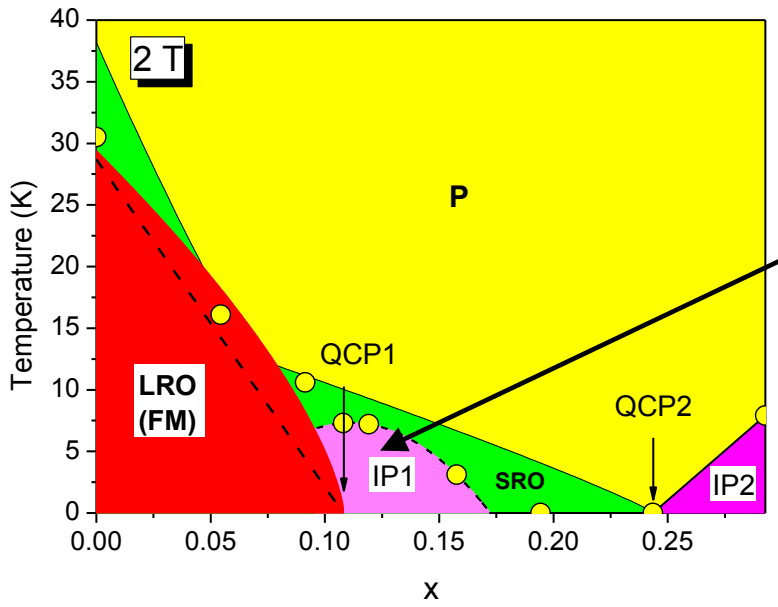
Magnetic phase diagram of MnSi in the high-field region

S. V. Demishev,* V. V. Glushkov, I. I. Lobanova, M. A. Anisimov, V. Yu. Ivanov, T. V. Ishchenko, M. S. Karasev, N. A. Samarin, N. E. Sluchanko, V. M. Zimin, and A. V. Semeno





Метод исследования магнитной фазовой диаграммы



Индуцированный магнитным полем переход внутри «голубой фазы»

ПЕРСПЕКТИВНЫЕ ЗАИМСТВОВАНИЯ ИЗ ФИЗИКИ ЖИДКИХ КРИСТАЛЛОВ

Жидкокристаллические параметры порядка при переходе в фазы с промежуточным магнитным порядком у Mn_{1-x} Fe_x Si.

Описание структуры фаз с промежуточным магнитным порядком.

Возможная анизотропия аналога «голубой фазы» у $Mn_{1-x}Fe_xSi$.

Управление фазами с промежуточным магнитным порядком с помощью магнитного поля для практических применений в области спинтроники.

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