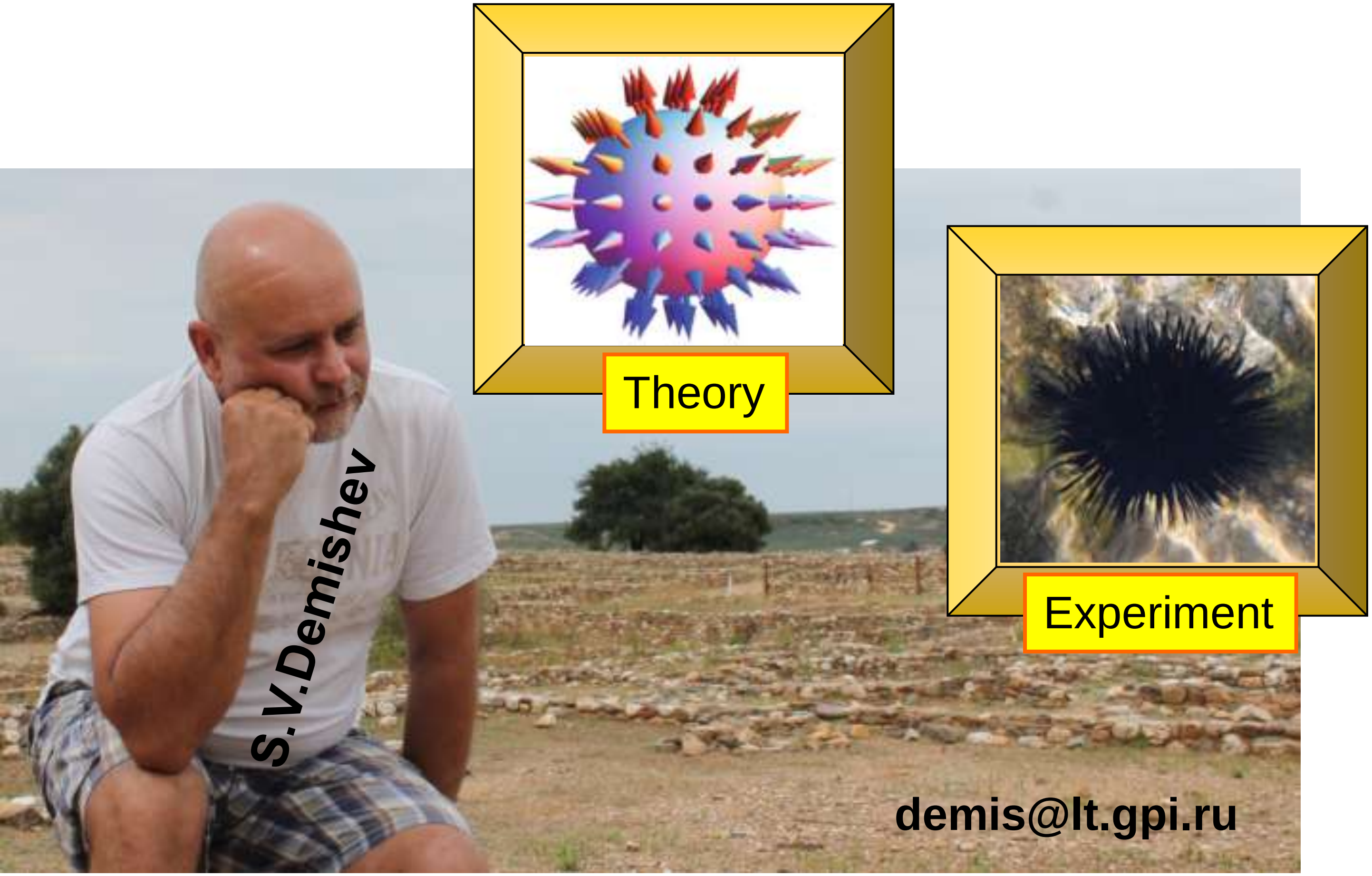
Magnetic vortexes and skyrmions in manganese monosilicide



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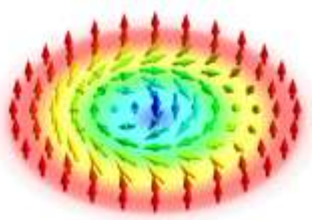
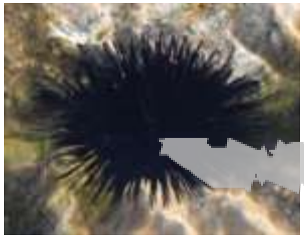
Vaviov street, 38, 119991 Moscow, Russia http://www.gpi.ru

Outline

- Introduction
- Skyrmion evolution





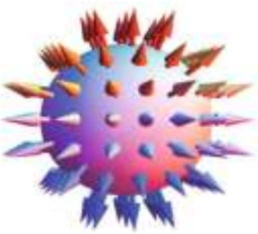
Experimental evidence for the existence of skyrmions in MnSi

Problems

Methods

Results

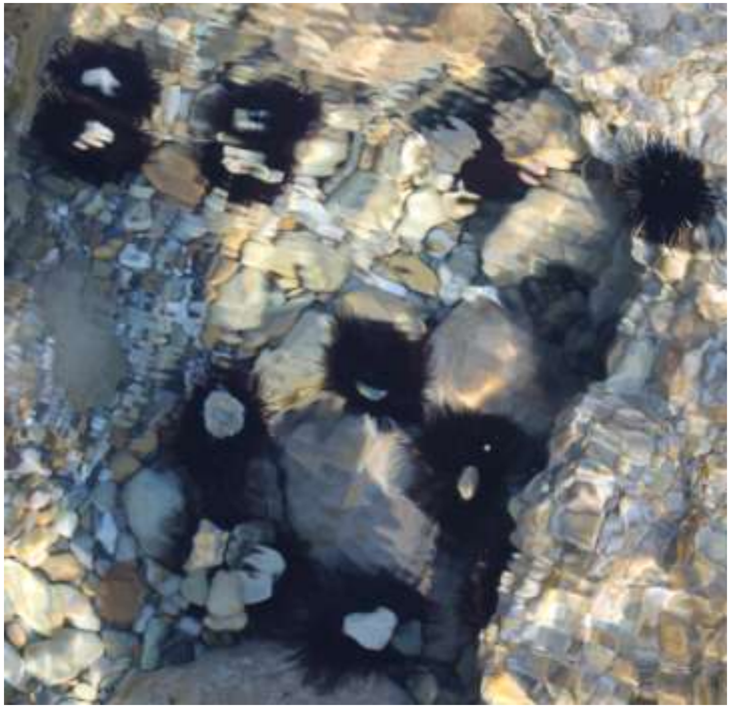
Discussion

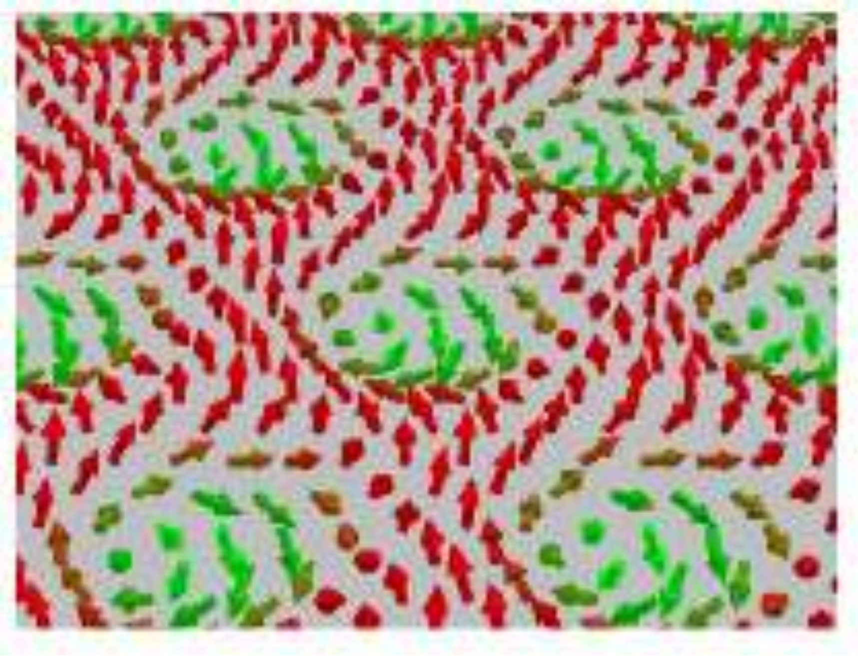


Introduction

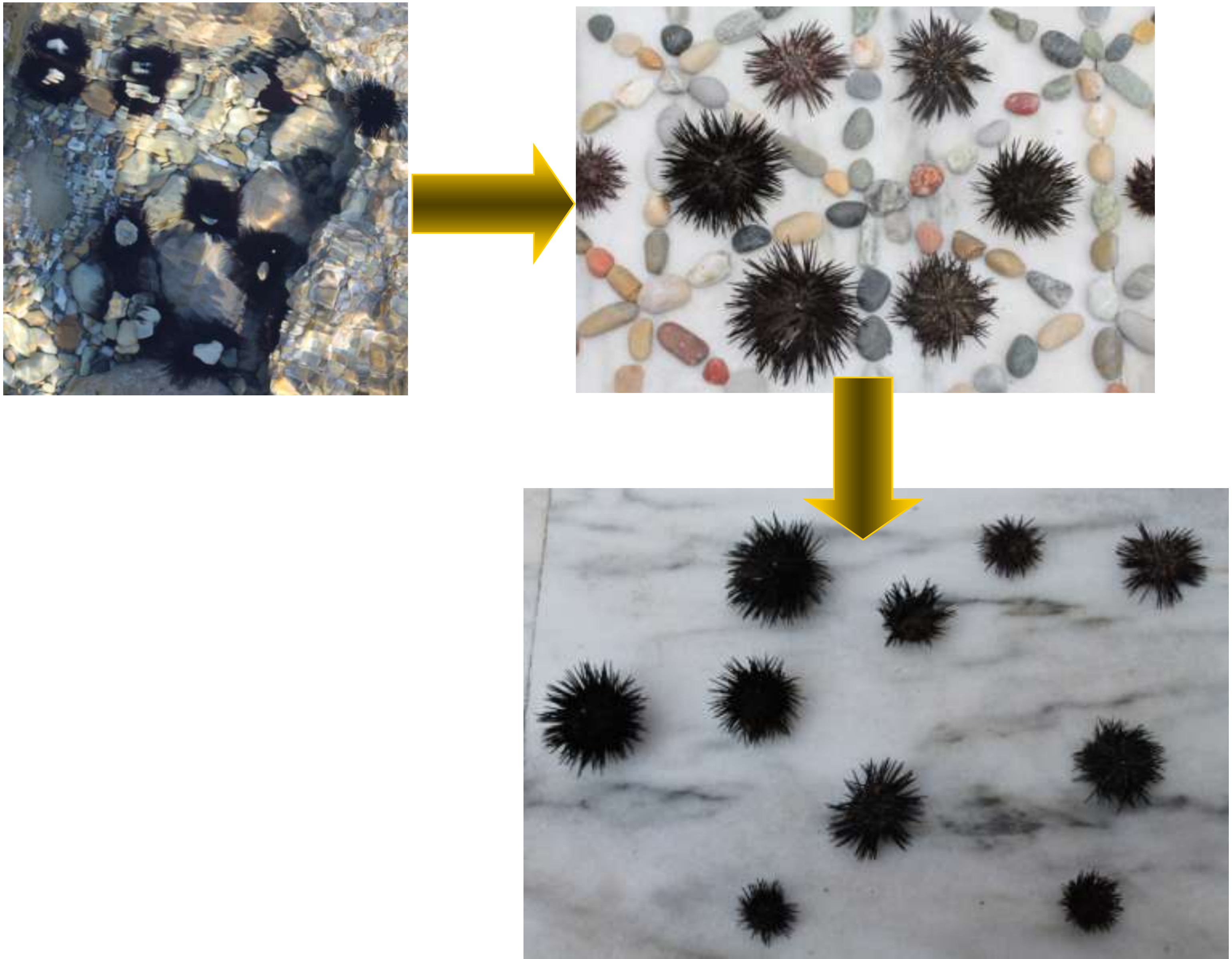
> **Пояснительные выражения объясняют тёмные мысли.**
>
> ***К.Прутков***

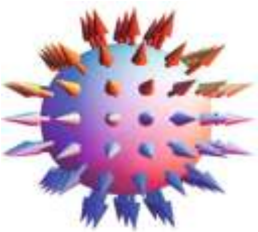
Blurred images and nice simulated pictures





Melting of a skyrmion lattice





Skyrmion evolution

Если на клетке слона прочтешь надпись «буйвол»,
не верь глазам своим.

К.Прутков

Skyrmions. The story begins…

Investigation of the transition of $FeCO_3$ from the antiferromagnetic to the paramagnetic state under the influence of a strong magnetic field

K. L. Dudko, V. V. Eremenko, and V. M. Fridman

Physico-technical Low Temperature Institute, Ukrainian Academy of Sciences

(Submitted July 17, 1974)
Zh. Eksp. Teor. Fiz. 68, 659–671 (February 1975)

$FeCO_3$, 1975

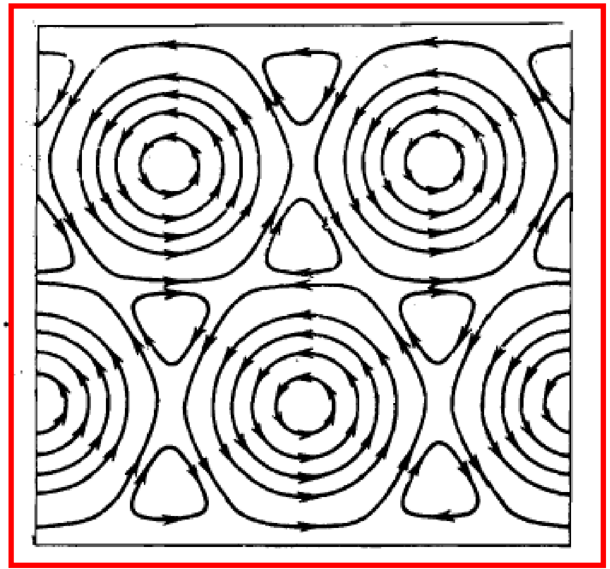
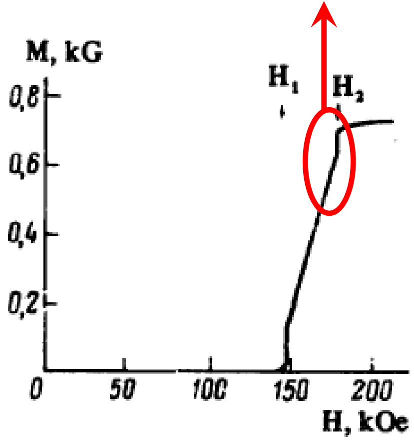
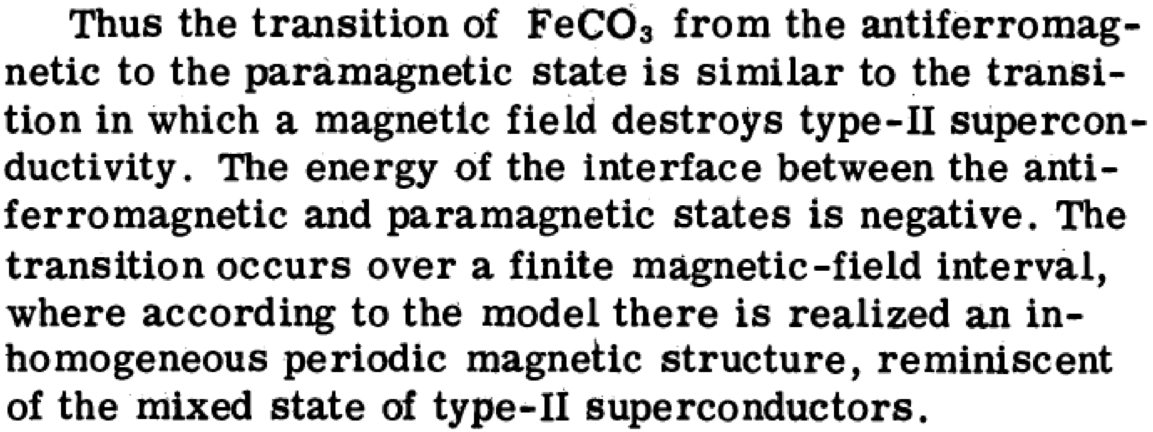


FIG. 4. Distribution of the effective exchange field produced by ions with reversed spins in the (111) plane.

Formation of the periodic inhomogeneous state (analogue to superconductors with $\sigma<0$) in vicinity of spin-flop transition.





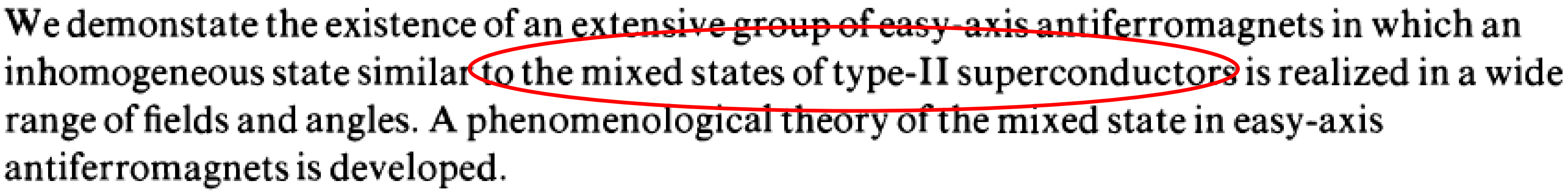
Thus the transition of $FeCO_3$ from the antiferromagnetic to the paramagnetic state is similar to the transition in which a magnetic field destroys type-II superconductivity. The energy of the interface between the antiferromagnetic and paramagnetic states is negative. The transition occurs over a finite magnetic-field interval, where according to the model there is realized an inhomogeneous periodic magnetic structure, reminiscent of the mixed state of type-II superconductors.

Skyrmions. The story continues…

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

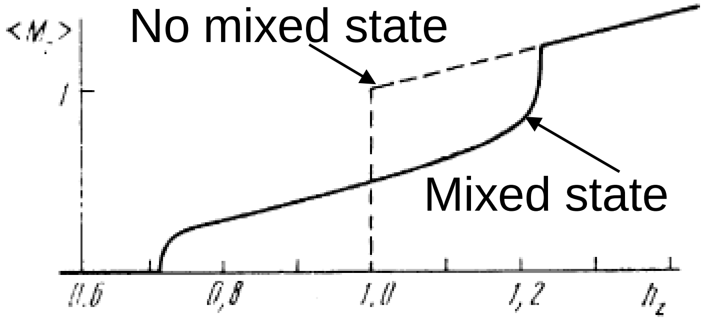
A. N. Bogdanov and D. A. Yablonskiĭ

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



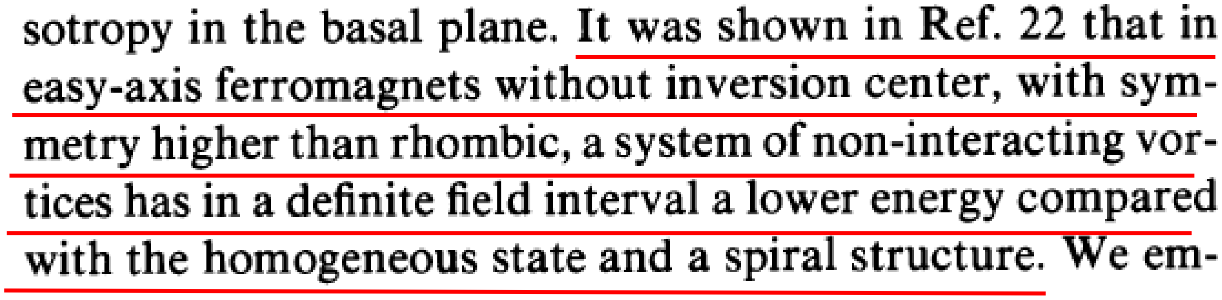
We demonstate the existence of an extensive group of easy-axis antiferromagnets in which an inhomogeneous state similar to the mixed states of type-II superconductors is realized in a wide range of fields and angles. A phenomenological theory of the mixed state in easy-axis antiferromagnets is developed.

Crystals without inversion center!



No mixed state

Mixed state



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-

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

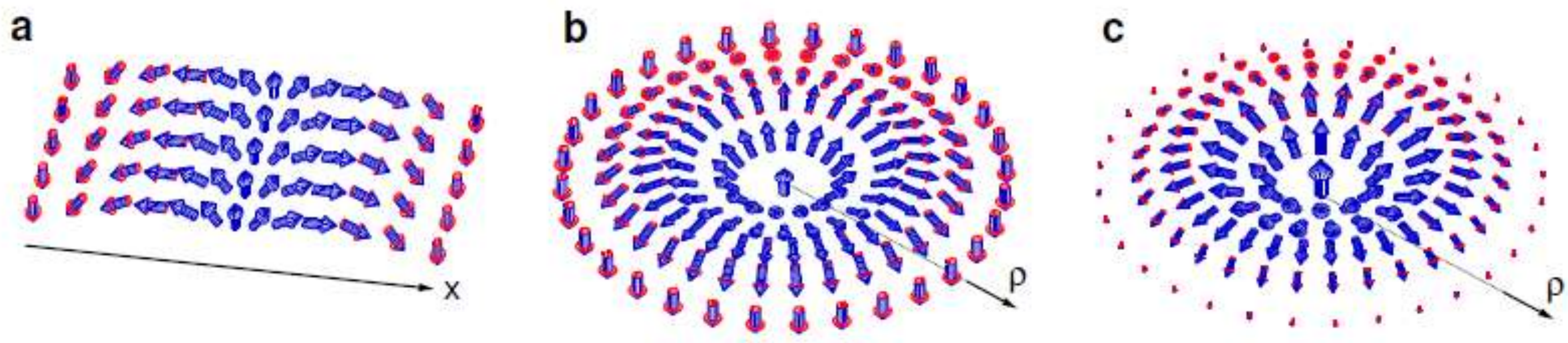
In the old times mixed state was thought to consist of Abrikosov-type vortixes.

Skyrmions. Now they are the knots in the vector field.

Nowadays “mixed” state is a skyrmion lattice (SL) 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(ρ→∞)|→0

Artificial skyrmions in film structures.

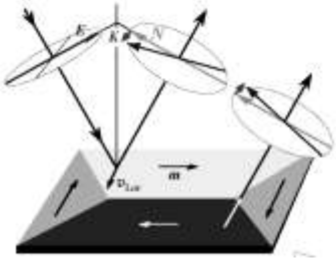
SCIENCE 17 JULY 2015 • VOL 349 ISSUE 6245

RESEARCH ARTICLE

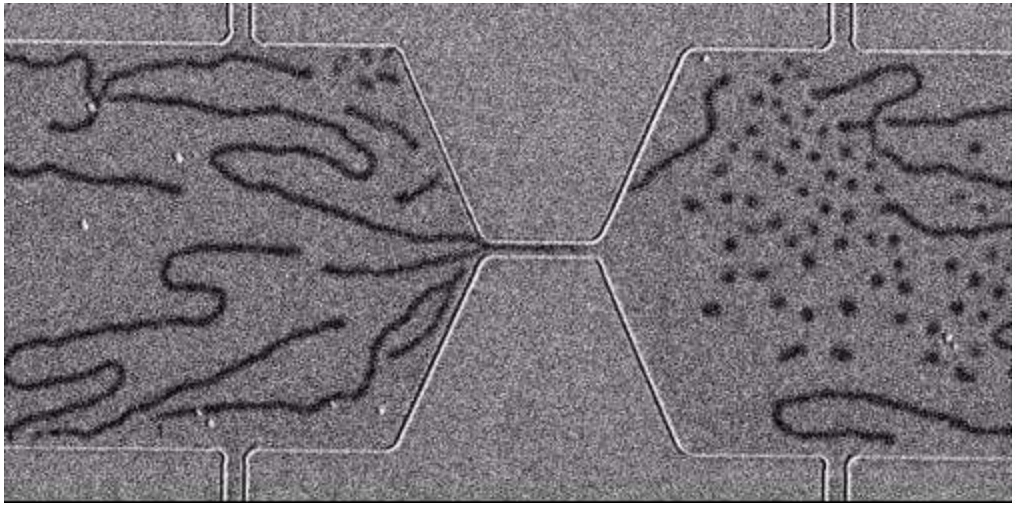
MAGNETISM

Blowing magnetic skyrmion bubbles

Wanjun Jiang,[1] Pramey Upadhyaya,[2] Wei Zhang,[1] Guoqiang Yu,[2]
M. Benjamin Jungfleisch,[1] Frank Y. Fradin,[1] John E. Pearson,[1] Yaroslav Tserkovnyak,[3]
Kang L. Wang,[2] Olle Heinonen,[1,4,5,6] Suzanne G. E. te Velthuis,[1] Axel Hoffmann[1]*



Ta(5 nm)/$Co_{20}Fe_{60}B_{20}$(CoFeB)(1.1 nm)/TaO_x(3 nm)

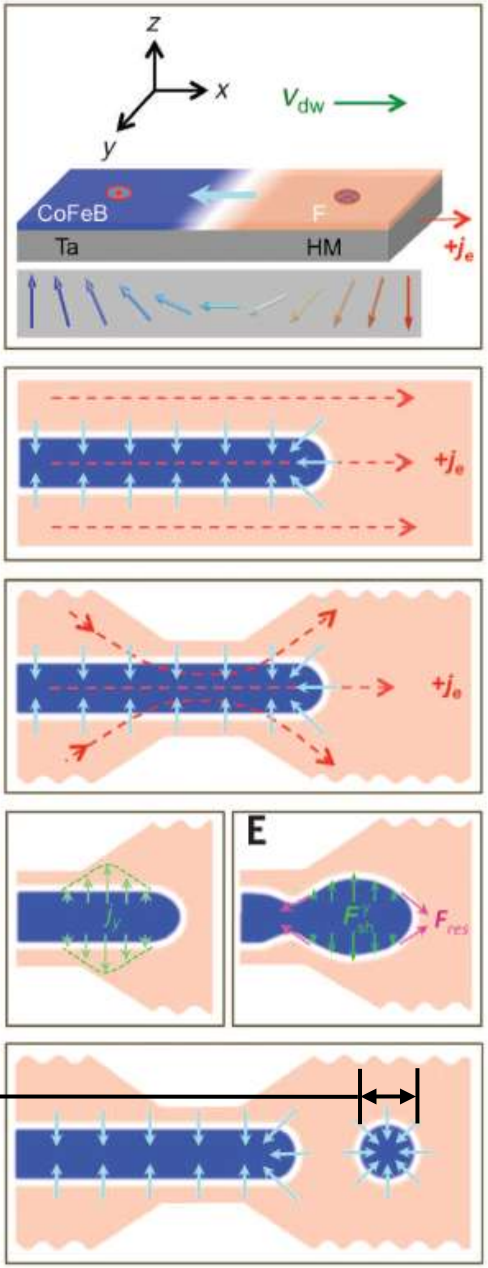


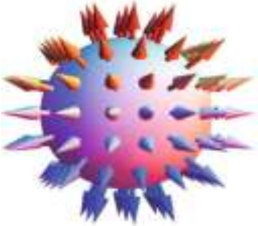
$j_e = +5 \times 10^5$ A/cm^2

↔ 20 μm

MOKE microscope image

700 nm – 2 μm





Experimental evidence for the existence of skyrmions in MnSi

Всякая вещь есть форма проявления беспредельного разнообразия.

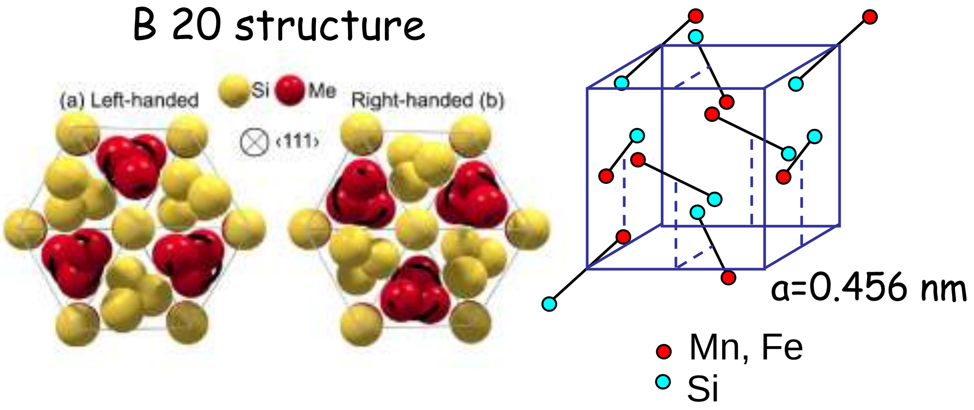
К.Прутков

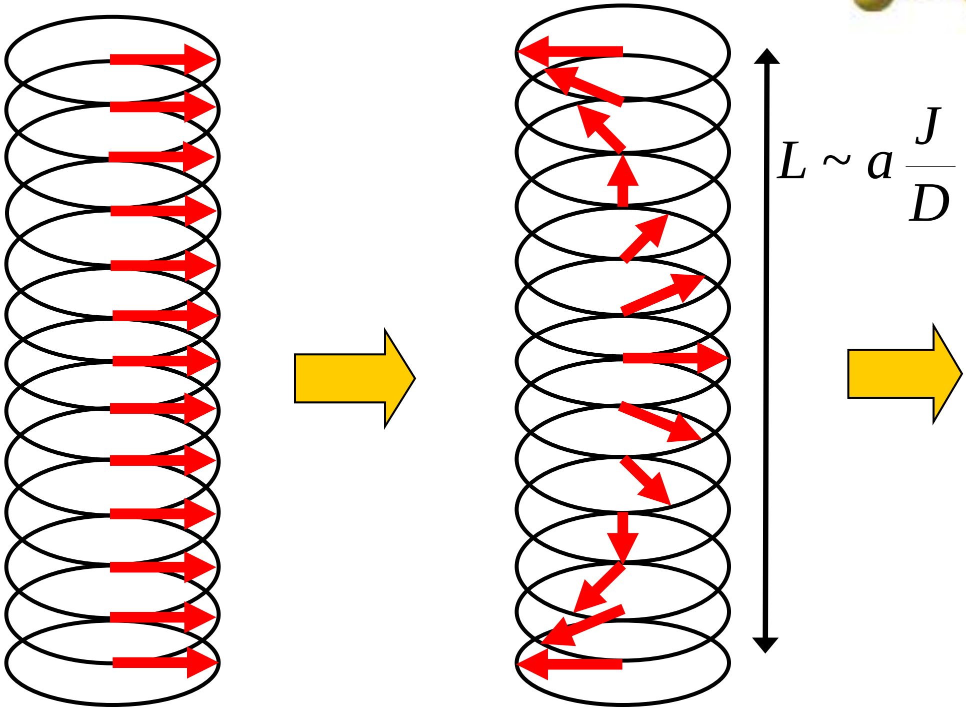
Chiral magnets $Mn_{1-x}Fe_xSi$.

Non-centrosymmetric magnets

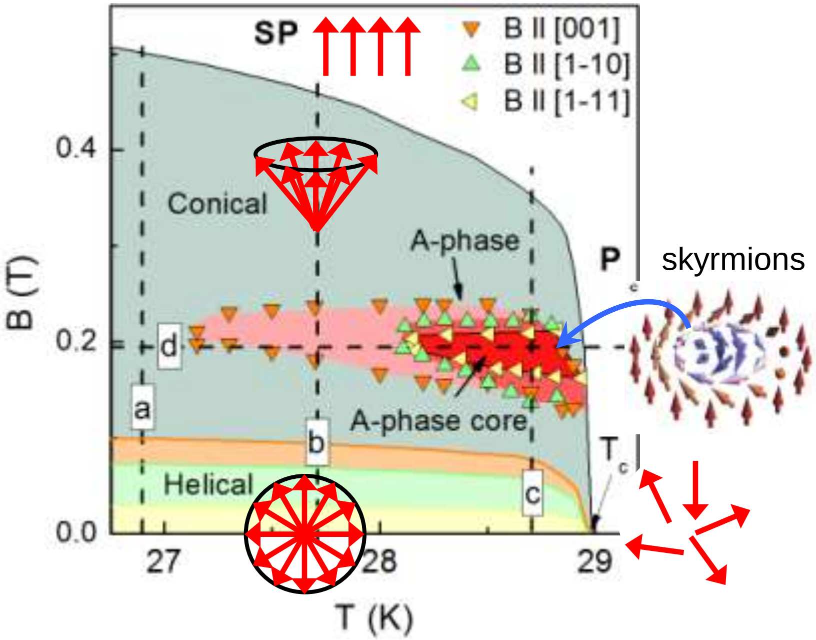
$$\hat{H} = \hat{H}_{EX} + \hat{H}_{DM} + \hat{H}_{Z}$$

B 20 structure





$$L \sim a\frac{J}{D}$$



$$\hat{H}_{EX} = -J\sum \vec{S}_i \cdot \vec{S}_j \qquad \hat{H}_{DM} = -D\sum \vec{S}_i \times \vec{S}_j$$

$$\hat{H}_Z = -\mu_B \vec{B} \sum \vec{S}_i$$

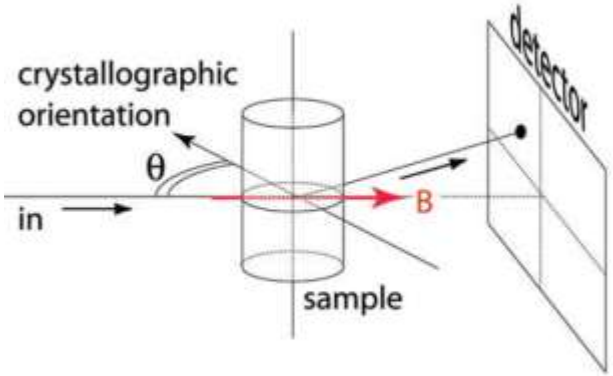
Experimental evidences for skyrmions in MnSi *(SANS).*

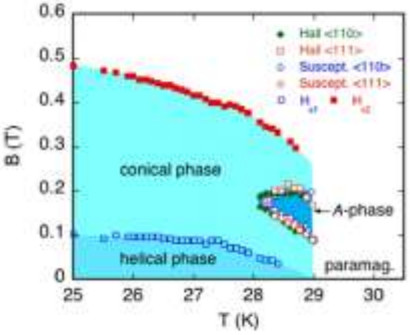
SCIENCE VOL 323 13 FEBRUARY 2009

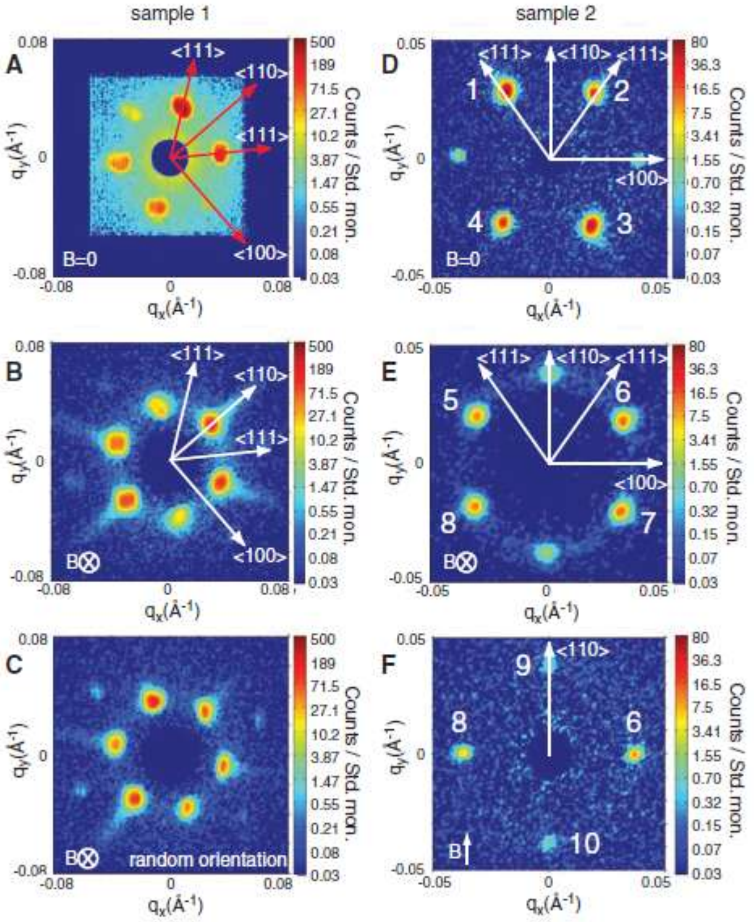
Skyrmion Lattice in a Chiral Magnet

S. Mühlbauer,[1,2] B. Binz,[3] F. Jonietz,[1] C. Pfleiderer,[1*] A. Rosch,[3]
A. Neubauer,[1] R. Georgii,[1,2] P. Böni[1]

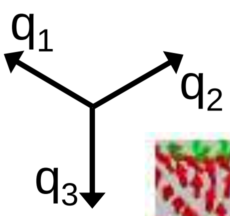
MnSi SANS

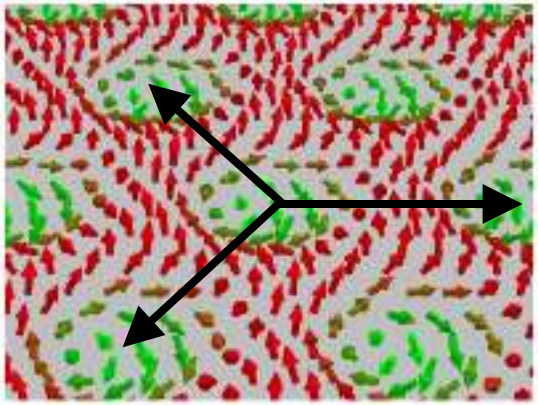






**A phase = Dense skyrmion phase
skyrmion lattice (SL)**





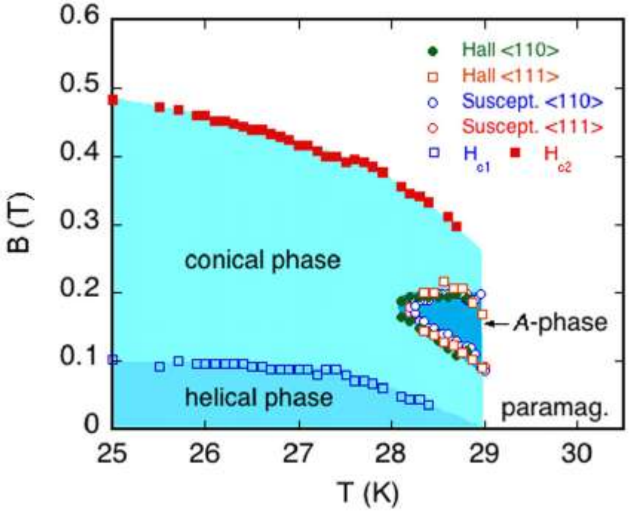
SL=Triple-q structure + Thermal (Gaussian) fluctuations

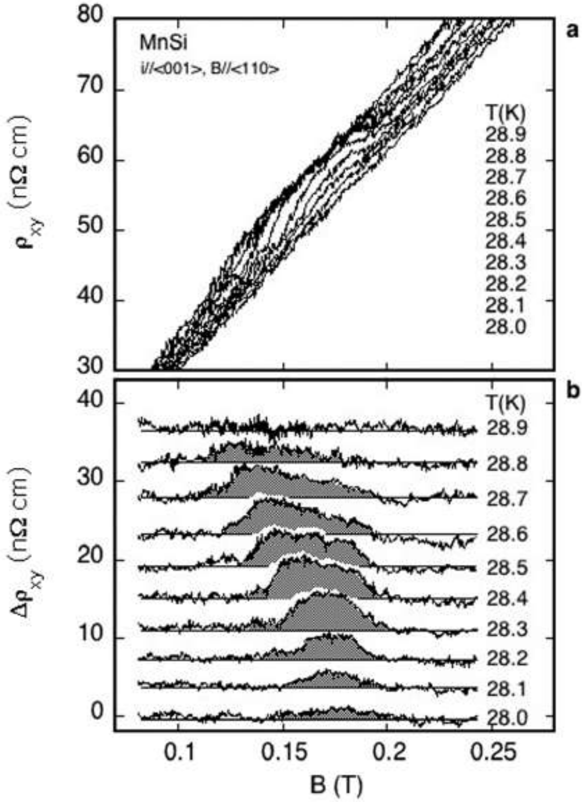
Experimental evidences for skyrmions in MnSi *(THE).*

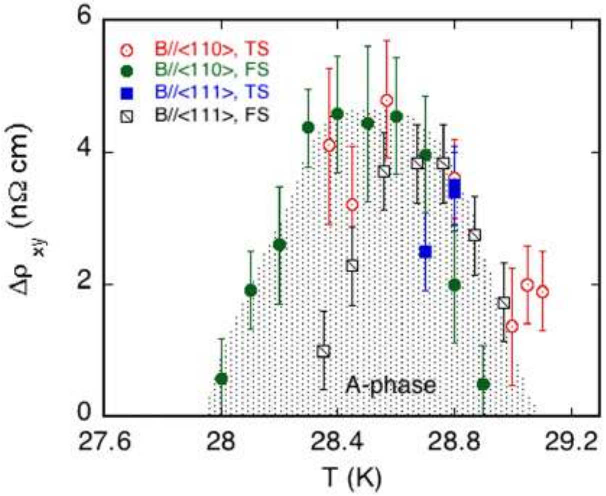
PRL **102,** 186602 (2009)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending
8 MAY 2009

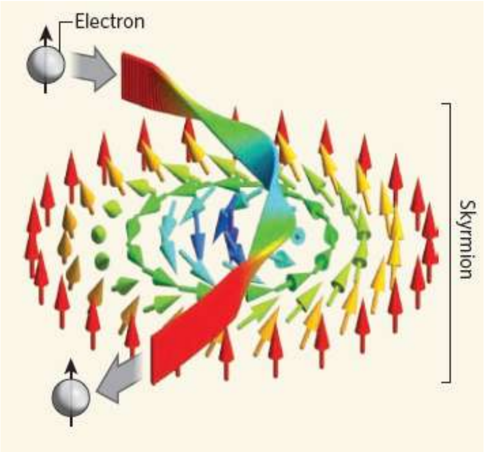
Topological Hall Effect in the *A* Phase of MnSi

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



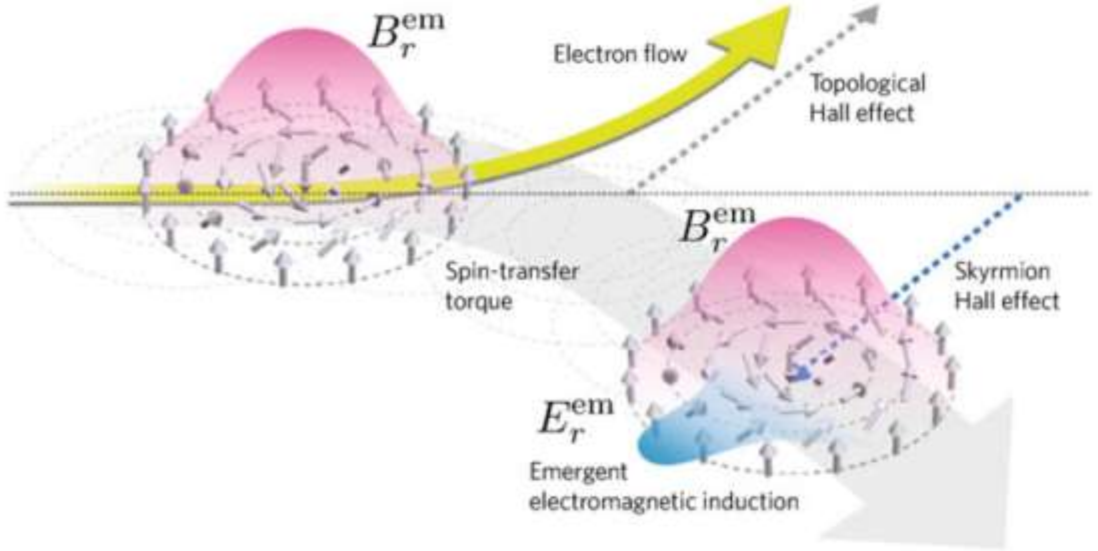






Topological Hall effect (THE) in A-phase of MnSi due to SL state

Skyrmions and topological Hall effect.



$$i\hbar\frac{\partial}{\partial t}\Psi = \left[\frac{p^2}{2m_\mathrm{e}} - J_\mathrm{ex}\boldsymbol{\sigma}\cdot\mathbf{m}(\mathbf{r},t)\right]\Psi \quad \Rightarrow \quad i\hbar\frac{\partial}{\partial t}\varphi = \left[\frac{(\mathbf{p}+e\mathbf{A}^\mathrm{s})^2}{2m_\mathrm{e}} - J_\mathrm{ex}\sigma_z - eV^\mathrm{s}\right]\varphi$$

$$B_i^{\mathrm{em}} = \epsilon_{ijk}\left(\partial_j A_k^\mathrm{s} - \partial_k A_j^\mathrm{s}\right) = \frac{\hbar}{2e}\epsilon_{ijk}\;\mathbf{m}\cdot(\partial_j\mathbf{m}\times\partial_k\mathbf{m})$$

$$E_i^{\mathrm{em}} = -\partial_i V^\mathrm{s} - \partial_t A_i^\mathrm{s} = \frac{\hbar}{e}\mathbf{m}\cdot(\partial_i\mathbf{m}\times\partial_t\mathbf{m})$$

$(\partial_i,\ \partial_j,\ \partial_k)=(\partial/\partial x,\ \partial/\partial y,\ \partial/\partial z)\qquad \partial_t=\partial/\partial t$

ϵ_{ijk} is the totally anti-symmetric tensor

$$\boxed{\begin{aligned}\rho_{xy} &= \rho_{xy}^{\mathrm{N}} + \rho_{xy}^{\mathrm{A}} + \rho_{xy}^{\mathrm{T}} \\ &= R_0 B + S_\mathrm{A}\rho_{xx}^2 M + PR_0 B_{rz}^{\mathrm{em}}\end{aligned}}$$

Band electron polarization rate

Experimental evidences for skyrmions in MnSi *(LTEM).*

NANO LETTERS

Nano Lett. 2012, 12, 1673−1677

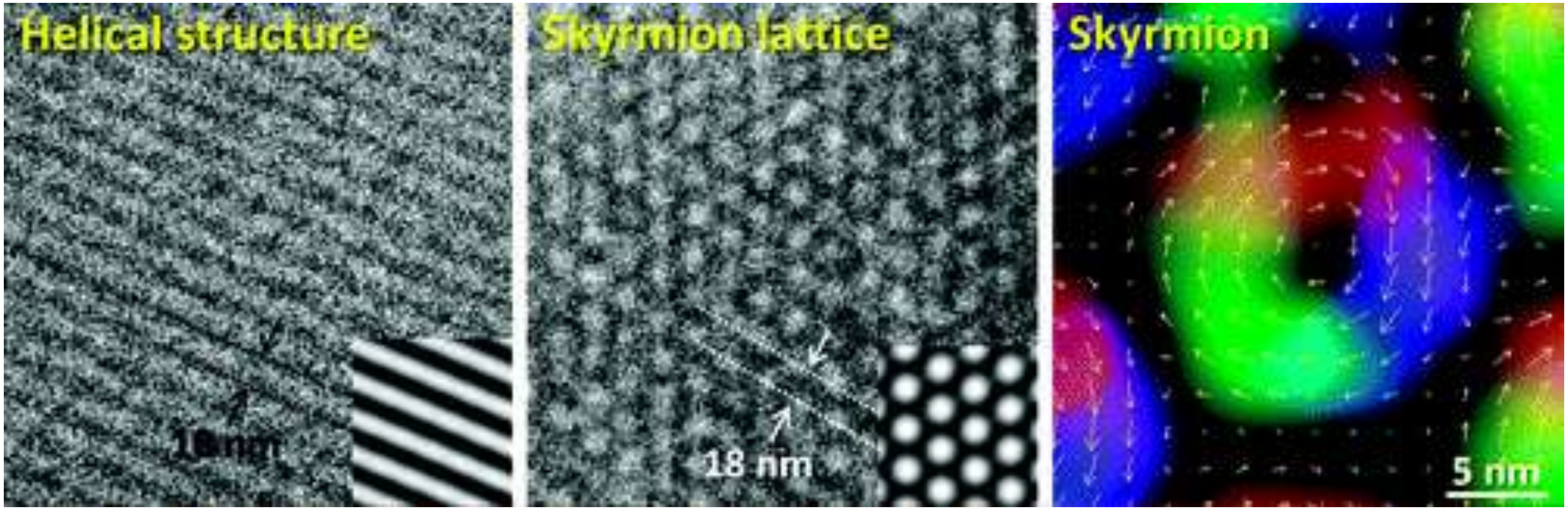
Letter

pubs.acs.org/NanoLett

Real-Space Observation of Skyrmion Lattice in Helimagnet MnSi Thin Samples

Akira Tonomura,[†,‡,§] Xiuzhen Yu,[†] Keiichi Yanagisawa,[‡] Tsuyoshi Matsuda,[∥] Yoshinori Onose,[⊥,¶] Naoya Kanazawa,[¶] Hyun Soon Park,[*,†] and Yoshinori Tokura[†,⊥,¶]

MnSi thin films obtained from single crystal + Lorentz TEM



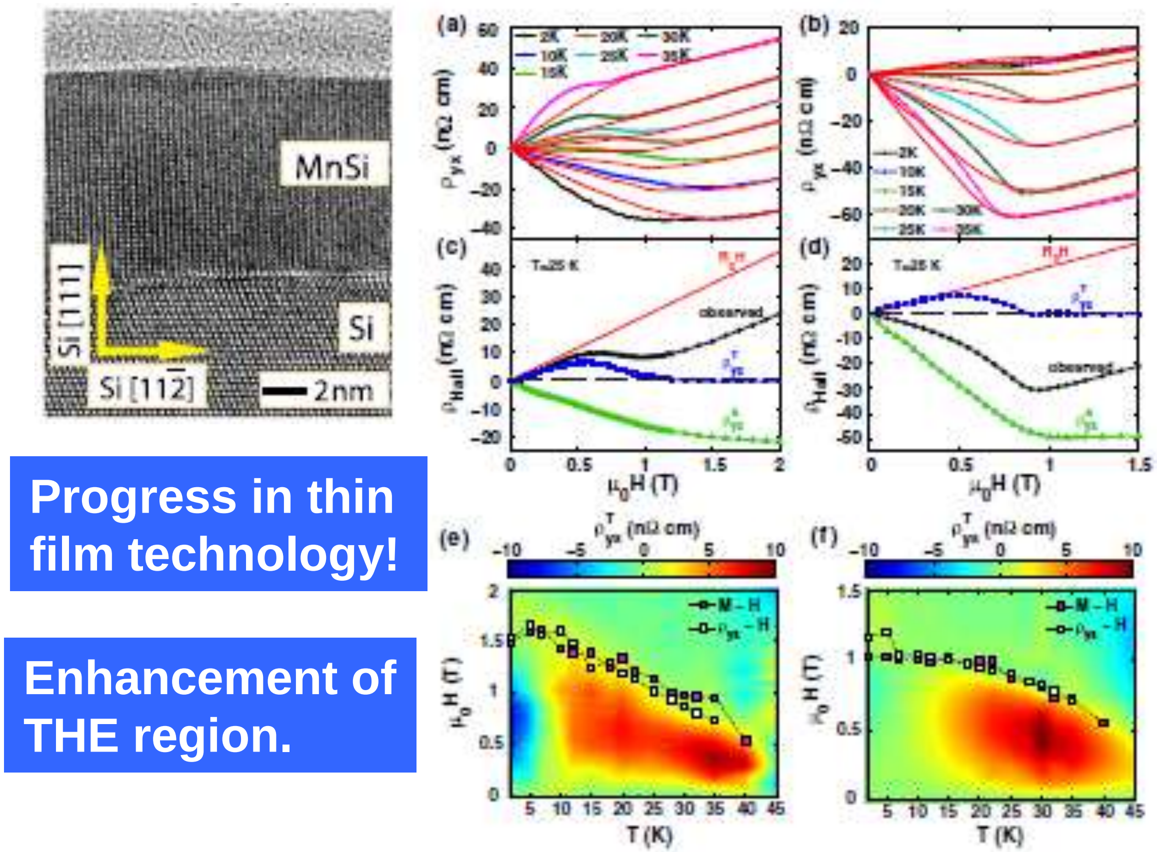
2012: Skyrmion lattice directly observed in A-phase. No direct evidence for single isolated skyrmions.

Skyrmions in MnSi *epitaxial films.*

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

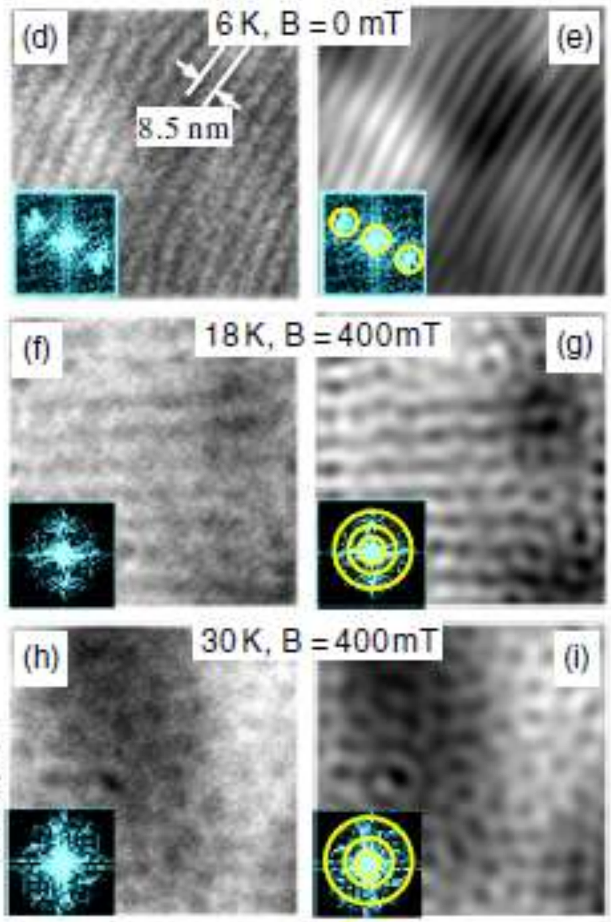
Yufan Li,[1,2] N. Kanazawa,[1] X. Z. Yu,[3] A. Tsukazaki,[1] M. Kawasaki,[1,3]
M. Ichikawa,[1] X. F. Jin,[2] F. Kagawa,[1] and Y. Tokura[1,3]



Progress in thin film technology!

Enhancement of THE region.

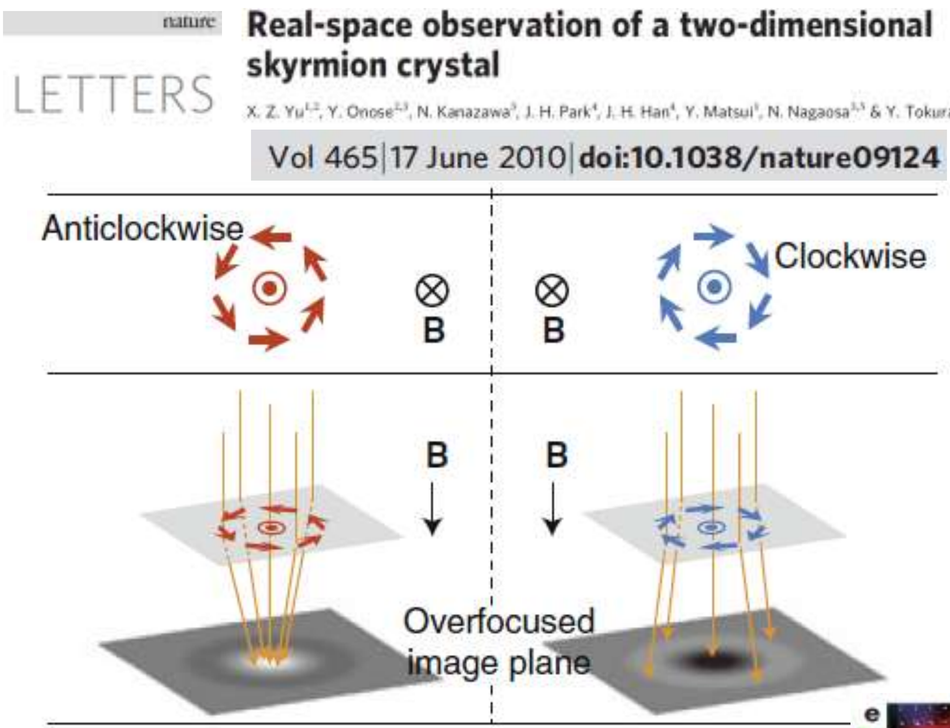
Disorder in skyrmion lattice



Skyrmions develops in THE area.

Measuring magnetic structure at the nanoscale.

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**

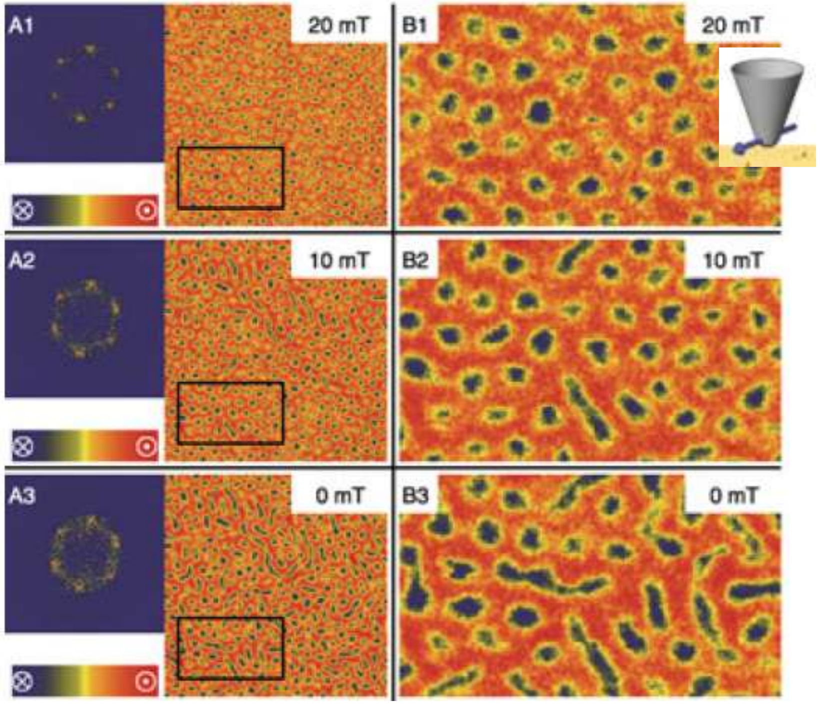
The contrast is due to deflection of the electrons by local magnetic fields.

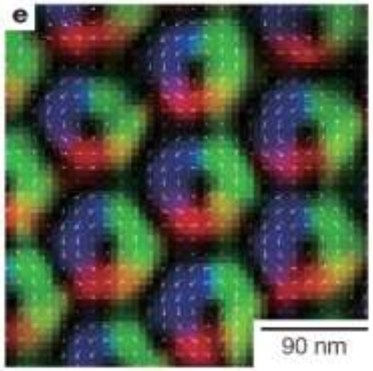
Somehow out of focus… Blurred image is unavoidable.

Thin films only!

SP-STM??

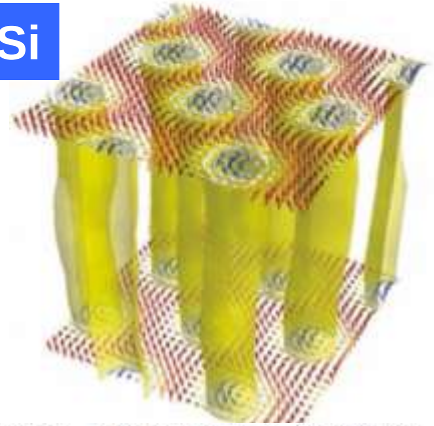
Magnetic force microscopy



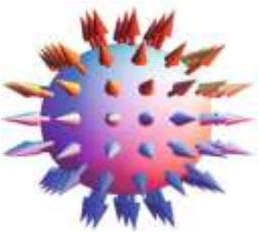


$Fe_{1-x}Co_xSi$

x=0.5



P. Milde, D. Köhler, J. Seidel, L.M. Eng, A. Bauer, A. Chacon, J. Kindervater, S. Mühlbauer, C. Pfleiderer, S. Buhrandt, C. Schütte, A. Rosch, Science **340**, 1076 (2013)

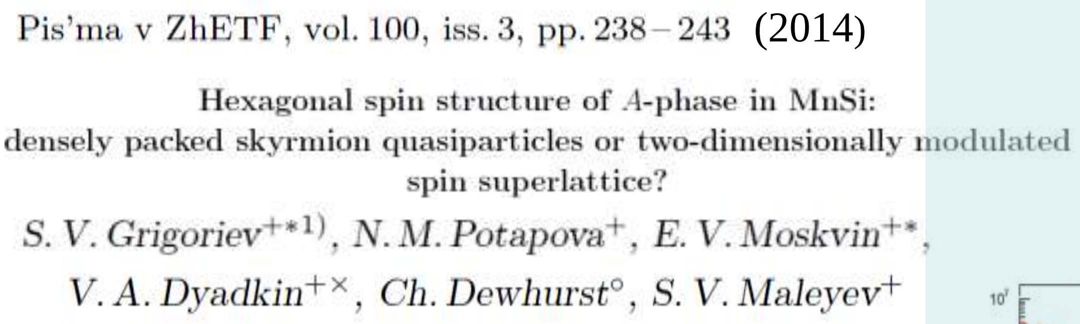


Problems

У многих катание на коньках производит отдышку и трясение.

К.Прутков

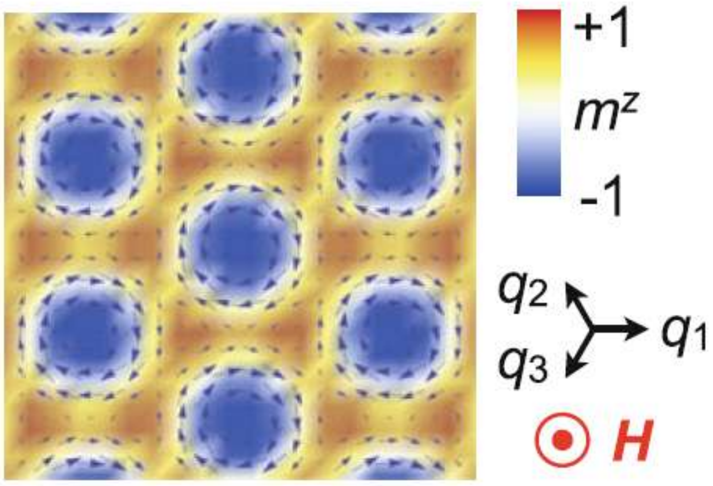
Grigoriev problem (SL vs. SL)



Pis'ma v ZhETF, vol. 100, iss. 3, pp. 238 – 243 (2014)

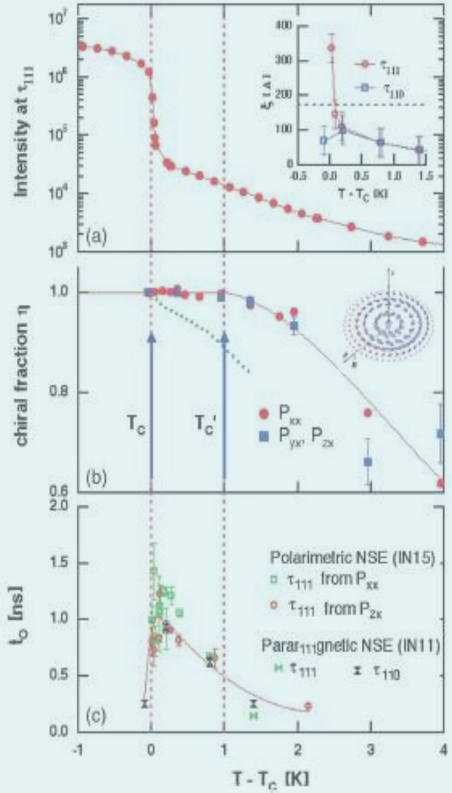
Hexagonal spin structure of *A*-phase in MnSi:
densely packed skyrmion quasiparticles or two-dimensionally modulated spin superlattice?

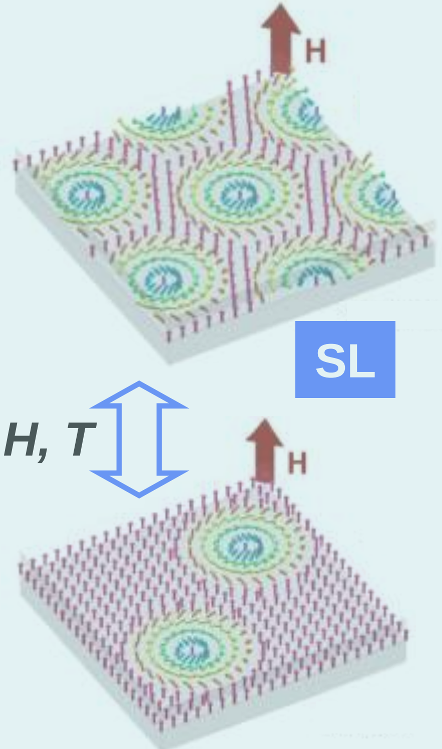
S. V. Grigoriev$^{+*1)}$, *N. M. Potapova*$^{+}$, *E. V. Moskvin*$^{+*}$,
V. A. Dyadkin$^{+\times}$, *Ch. Dewhurst*$^{\circ}$, *S. V. Maleyev*$^{+}$



Triple-q SL= complicated magnetic phase with anisotropic phase boundaries (coupled to crystal magnetic anisotropy)

SL is a result of condensation of individual skyrmions (quasiparticles)





SL

Individual skyrmions

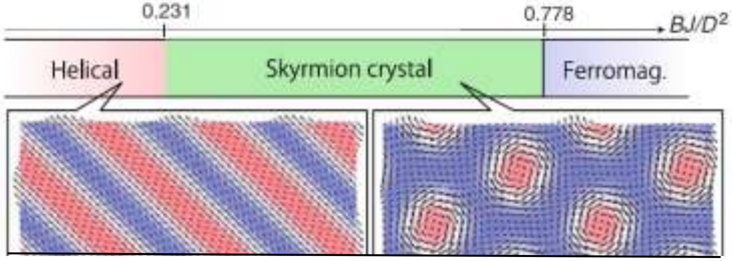
PRL **102**, 197202 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

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]

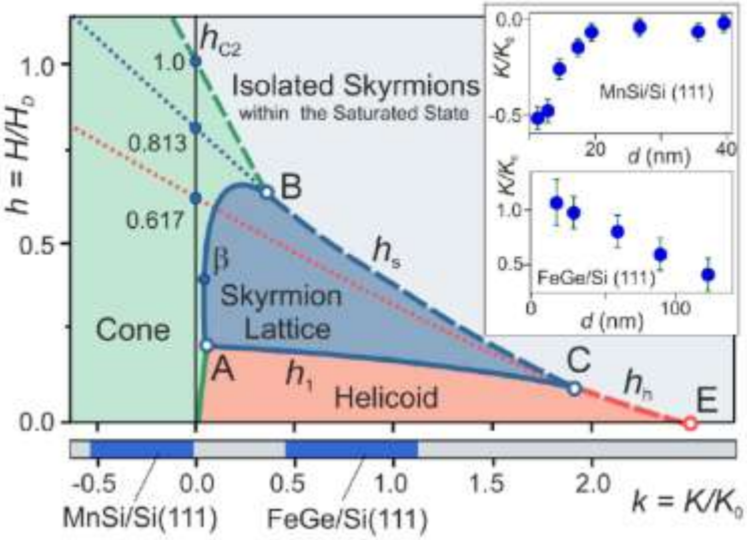
Skyrmion stability problem (Monchesky et al. vs. Tokura et al.)

2D Heisenberg



WILSON, BUTENKO, BOGDANOV, AND MONCHESKY

PHYSICAL REVIEW B **89**, 094411 (2014)



XIUZHEN YU *et al.*

PHYSICAL REVIEW B **91**, 054411 (2015)

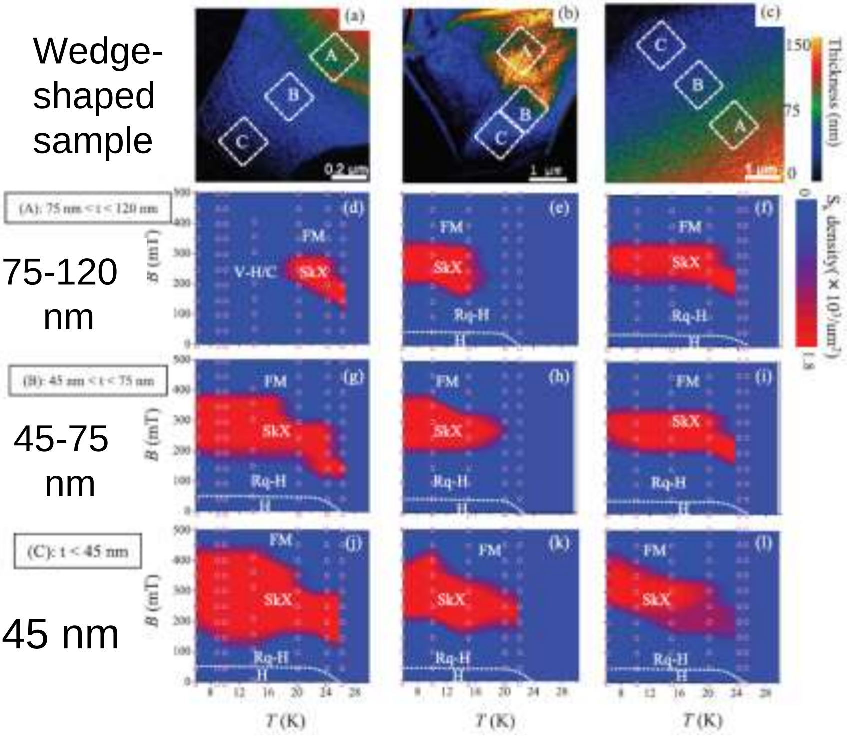
(111) (110) (001)

Wedge-shaped sample

75-120 nm

45-75 nm

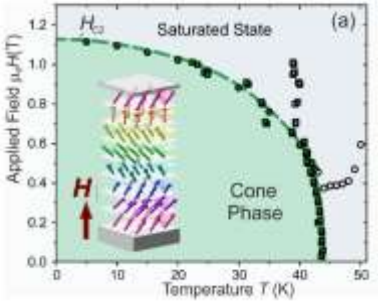
<45 nm

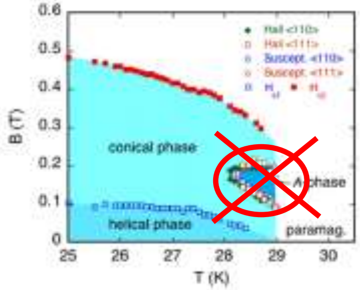


Stability in

3D??

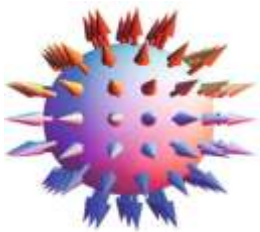
2D??





A-phase in bulk MnSi is totally metastable, and is not real magnetic phase.
Metastability is evidenced by magnetoresistance hysteresis.

Kazuo KADOWAKI, Kiichi OKUDA* and Muneyuki DATE
Journal of the Physical Society of Japan
Vol. 51, No. 8, August, 1982, pp. 2433–2438



Methods

Барометр в земледельческом хозяйстве может быть с большою выгодою заменен усердную прислугою, страдающею нарочитыми ревматизмами.

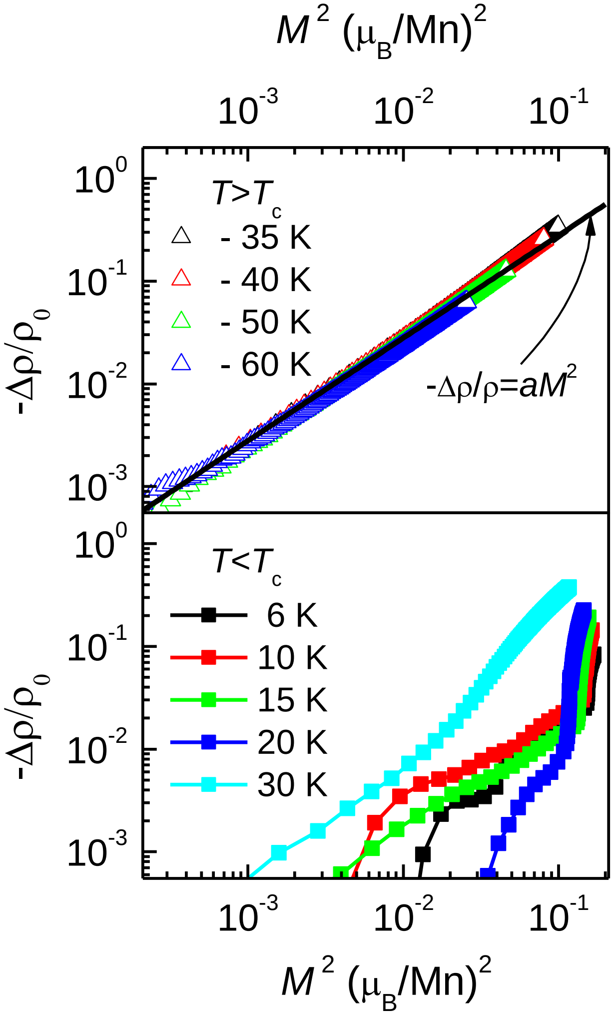
К.Прутков

Experimental tools for SL study. Magnetic scattering in MnSi.

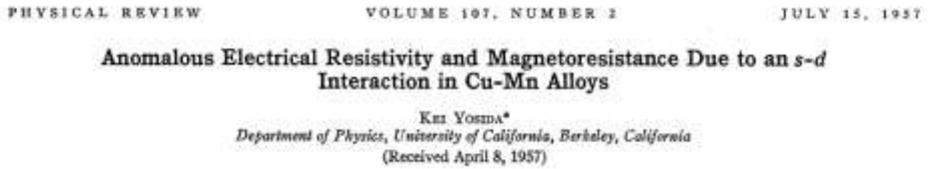
PHYSICAL REVIEW B 85, 045131 (2012)

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)



In MnSi scattering on the localized magnetic moments completely controls magnetoresistance even in the paramagnetic phase.



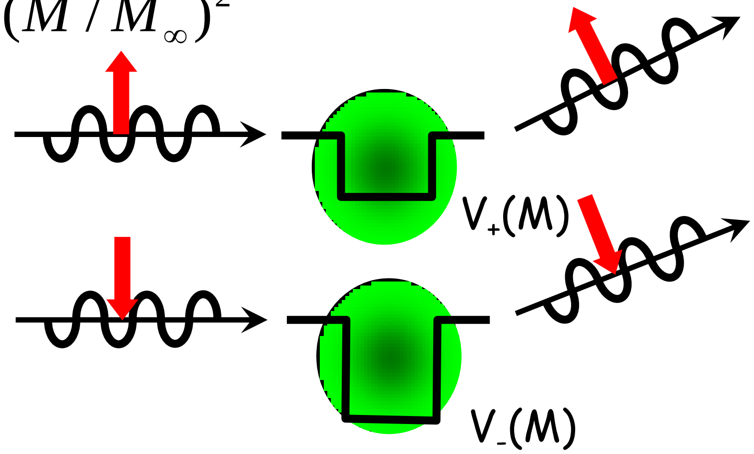
PHYSICAL REVIEW VOLUME 107, NUMBER 2 JULY 15, 1957

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)

Yosida universal scaling in the paramagnetic phase:

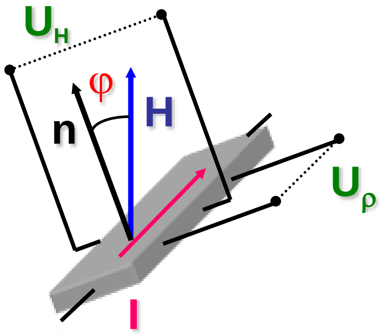
$$\Delta\rho/\rho = -a_0(M/M_\infty)^2$$

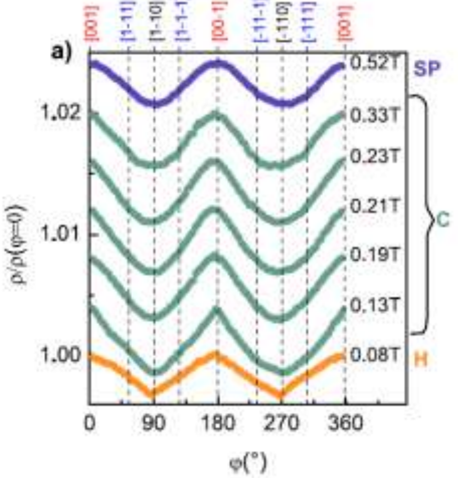


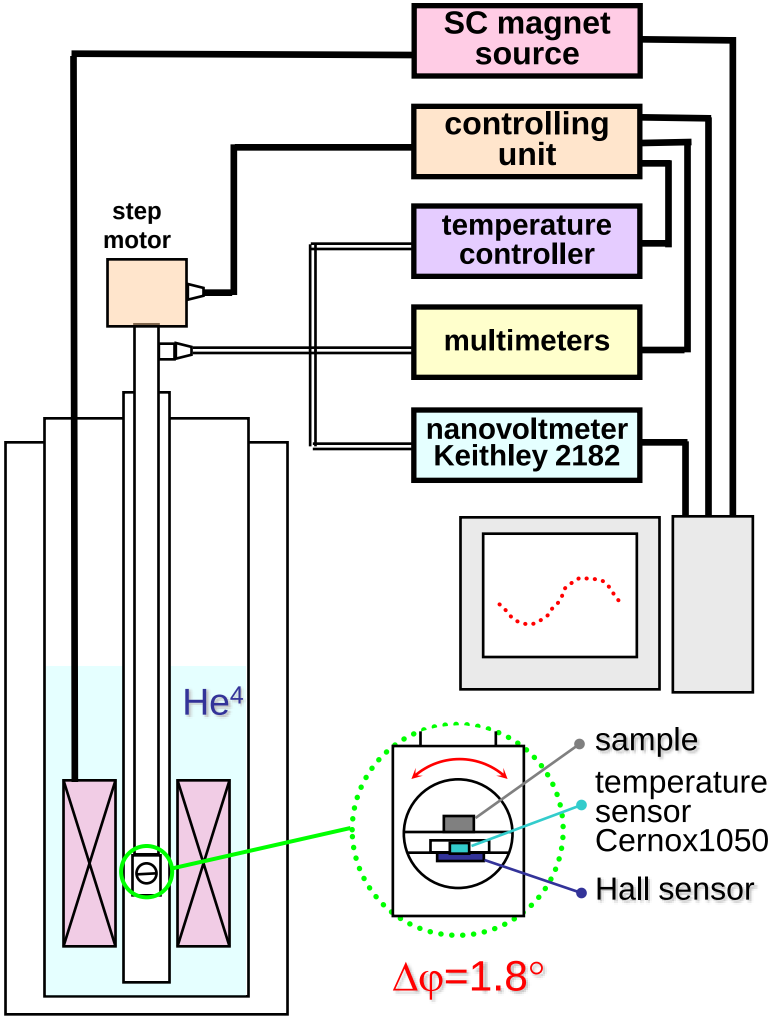
Peculiarities of the magnetoresistance may be used for studying of the magnetic phase diagram.

Experimental tools for SL study. Experimental setup.

Step rotation of the sample in magnetic field







SC magnet source

controlling unit

temperature controller

multimeters

nanovoltmeter Keithley 2182

step motor

He^4

sample

temperature sensor Cernox1050

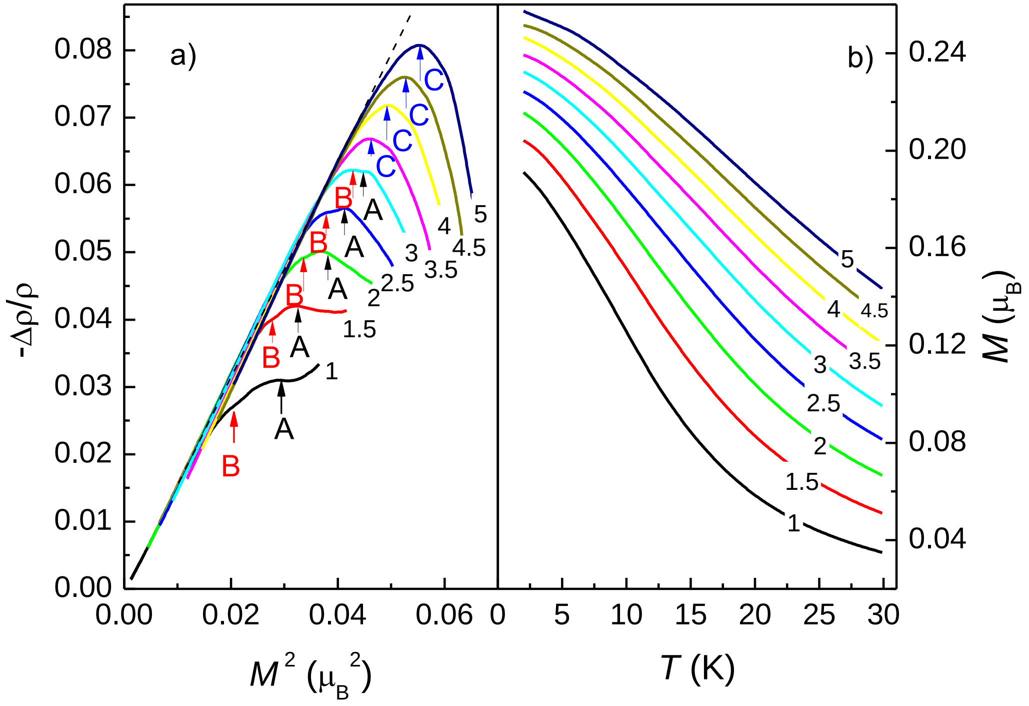
Hall sensor

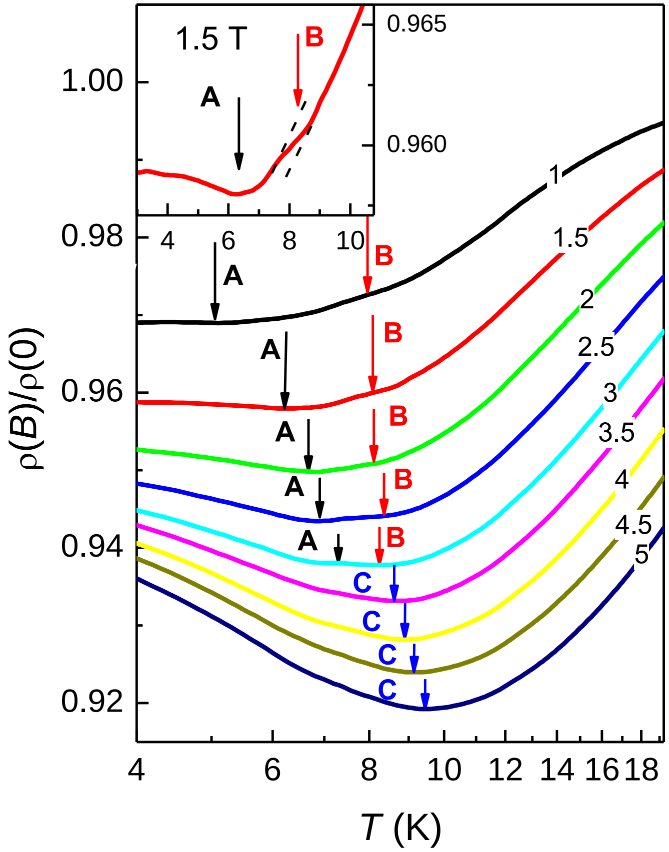
$\Delta\varphi=1.8°$

Magnetic field: 8 T (14 T)
Field stability $2{\cdot}10^{-5}$
Temperature: 1.8-300 K
Temperature stability: 1 mK (T<40 K)
Sample rotation: $\pm 360^0$
Resistivity relative accuracy: 10^{-5} (DC) 10^{-6} (AC)

$Mn_{1-x}Fe_xSi$ sample with x=0.108. Magnetoresistance.

Use of magnetic scattering for establishing of the magnetic phase diagram.





Paramagnetic phase is marked by universal scaling $\Delta\rho/\rho = - M(B,T)^2$.

Positions of negative magnetoresistance minima mark transitions into magnetically ordered phases.

Pis'ma v ZhETF, vol. 103, iss. 5, pp. 365 – 371 © 2016 March 10

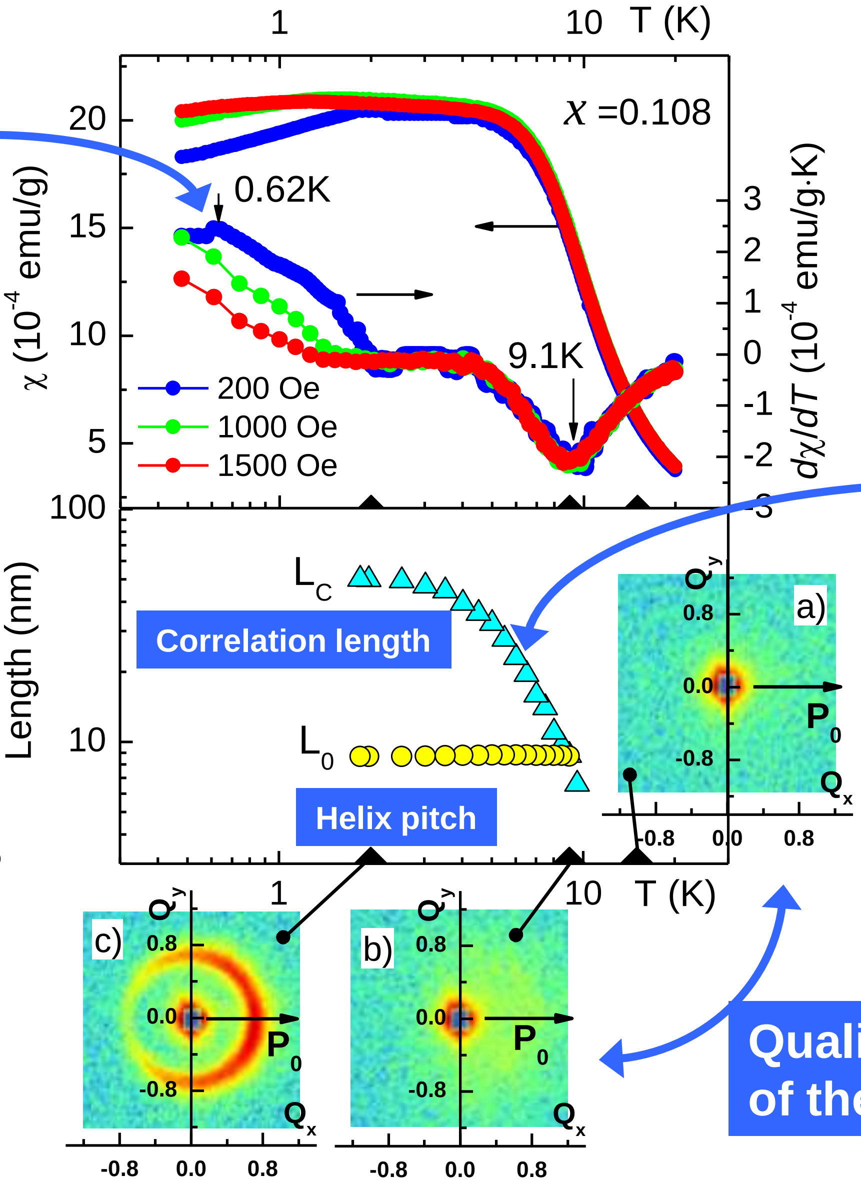
Effect of magnetic field on the intermediate phase in $Mn_{1-x}Fe_xSi$:
spin-liquid vs. fluctuations scenario

S. V. Demishev[a,b1)], I. I. Lobanova[a,b], A. V. Bogach[a], V. V. Glushkov[a,b], V. Yu. Ivanov[a], T. V. Ischenko[a], N. A. Samarin[a], N. E. Sluchanko[a], S. Gabani[c], E. Čižmár[d], K. Flachbart[c], N. M. Chubova[e], V. A. Dyadkin[e,f], S. V. Grigoriev[e]

$Mn_{1-x}Fe_xSi$ sample with x=0.108. SANS and susceptibility.

Susceptibility down to very low temperatures and small angle neutron scattering (SANS) data.

Low temperature transition into spiral LRO phase

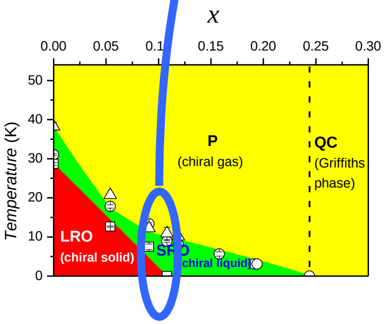


Correlation length

Helix pitch

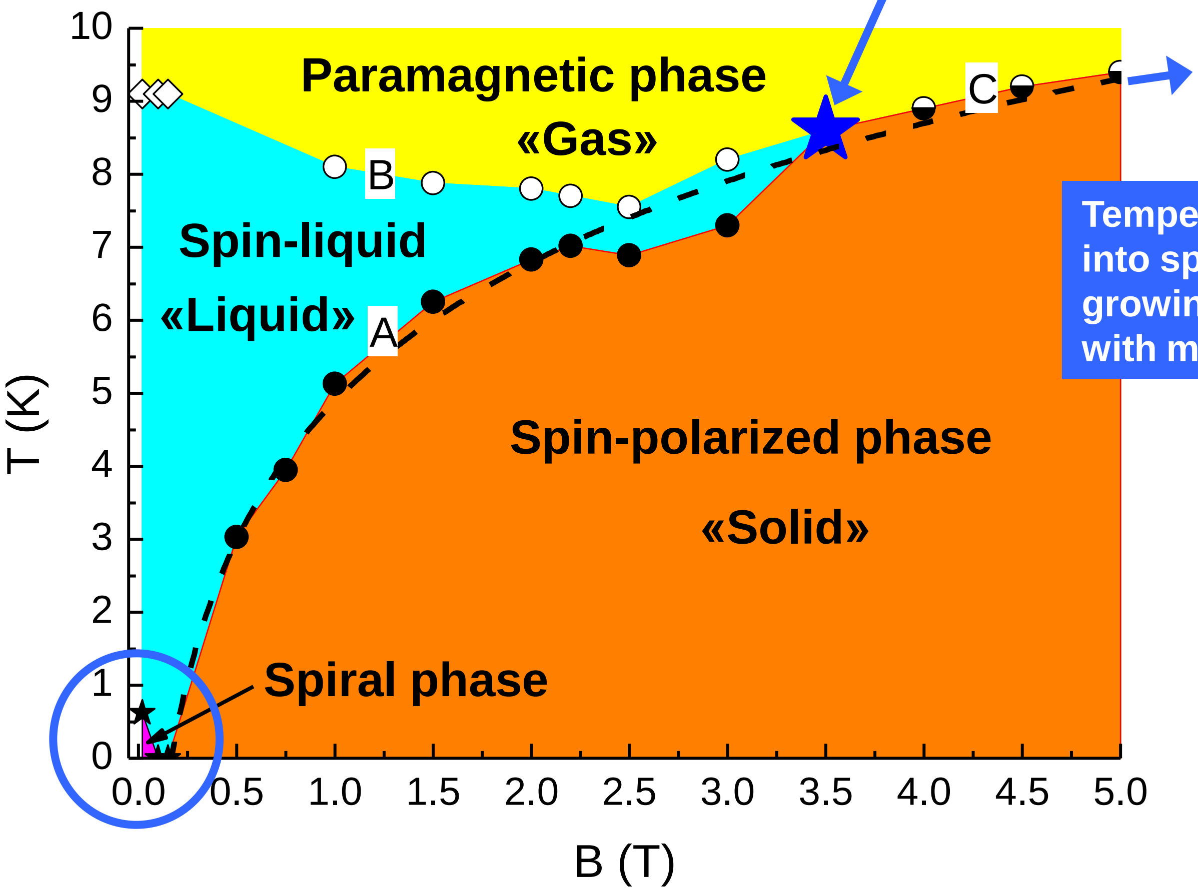
Fluctuations vs. spin liquid

Qualitative change of the SANS map



Chiral spin-liquid in magnetic field. Two transitions into “Solid” phase

Singular point



$$T_{SP} \approx T_0 \log(B/B_0)$$

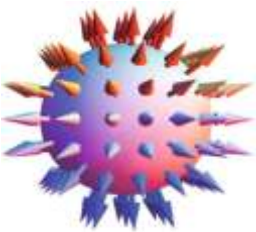
$$T_0 = 2.7\ \mathrm{K},\ B_0 = 0.17\ \mathrm{T}$$

Temperature of the transition into spin-polarized phase growing logarithmically with magnetic field.

New QC point?

Spin liquid is more robust with respect to magnetic field than spiral phase with the magnetic LRO.

There is singular point B~3.5 T and T~8.5 K on the magnetic phase diagram.



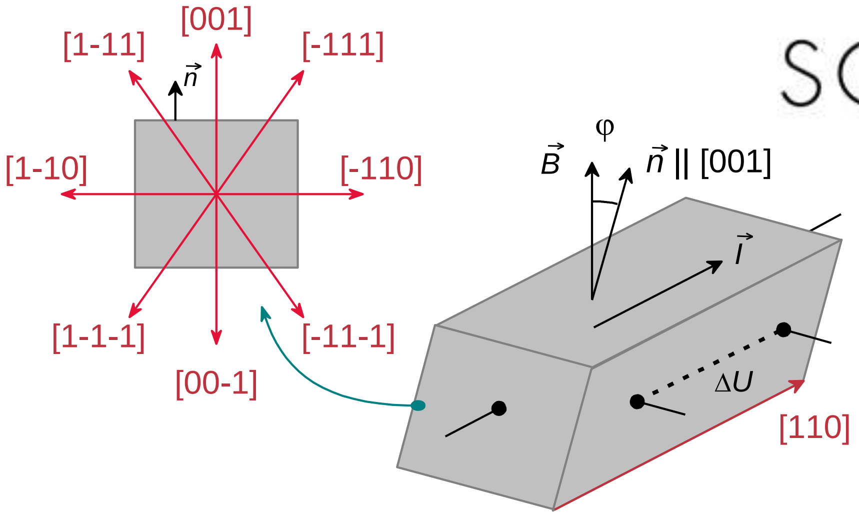
Results

Не в совокупности ищи единства, но более в единообразии разделения.

К.Прутков

Experimental results.

Experimental geometry



www.nature.com/scientificreports

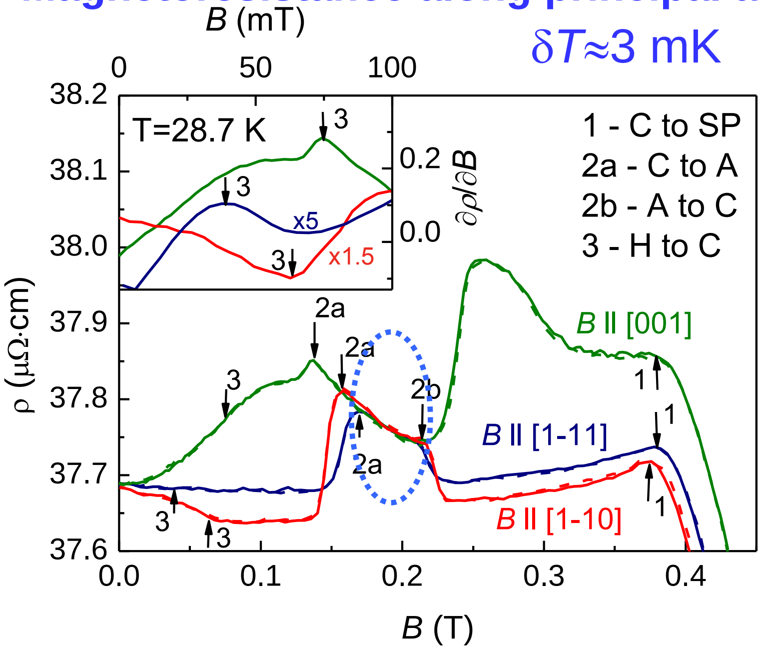
SCIENTIFIC REPORTS

Macroscopic evidence for Abrikosov-type magnetic vortexes in MnSi *A*-phase

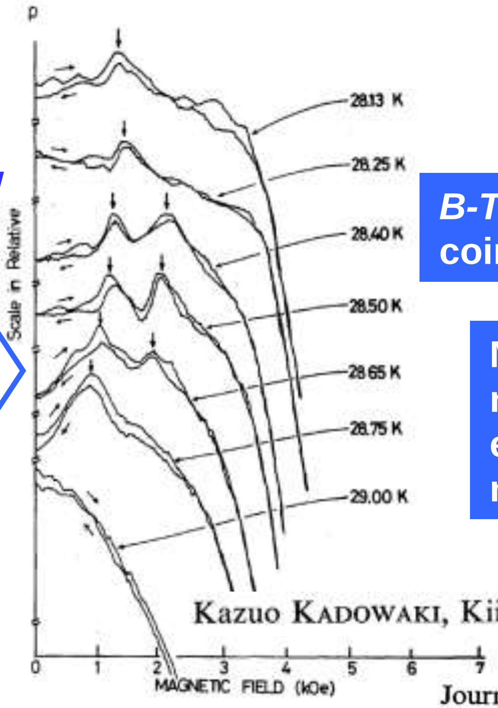
I. I. Lobanova[1], V. V. Glushkov[1,2], N. E. Sluchanko[1,2] & S. V. Demishev[1,2]

SCIENTIFIC REPORTS | 6:22101 | DOI: 10.1038/srep22101

Magnetoresistance along principal axes



New vs. Old



Kazuo KADOWAKI, Kiichi OKUDA* and Muneyuki DATE

Journal of the Physical Society of Japan
Vol. 51, No. 8, August, 1982, pp. 2433–2438

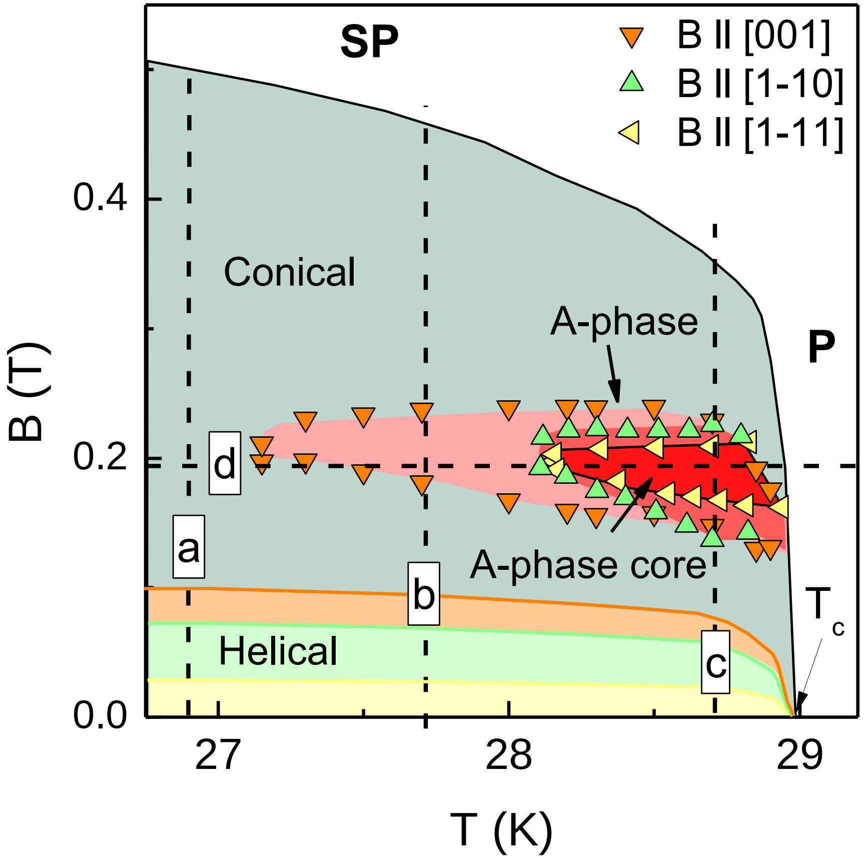
No hysteresis!

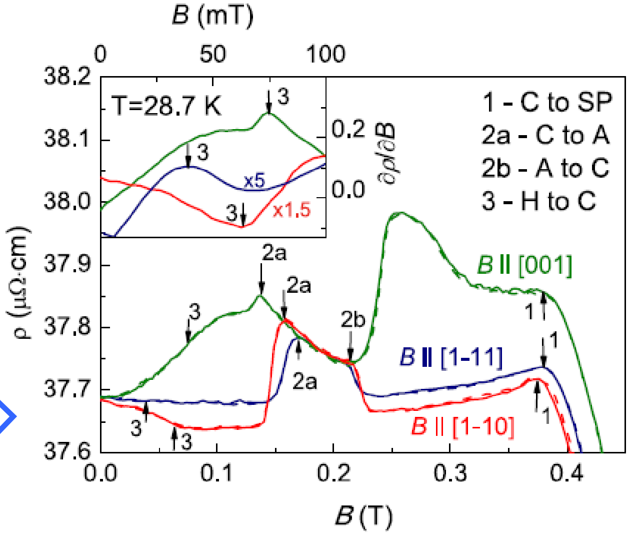
***B-T* region where resistivity coincide for three directions**

Magnetoresistance kinks may be used for establishing magnetic phase diagram

Experimental results. MnSi *magnetic phase diagram.*

Magnetic phase diagram from magnetoresistance measurements



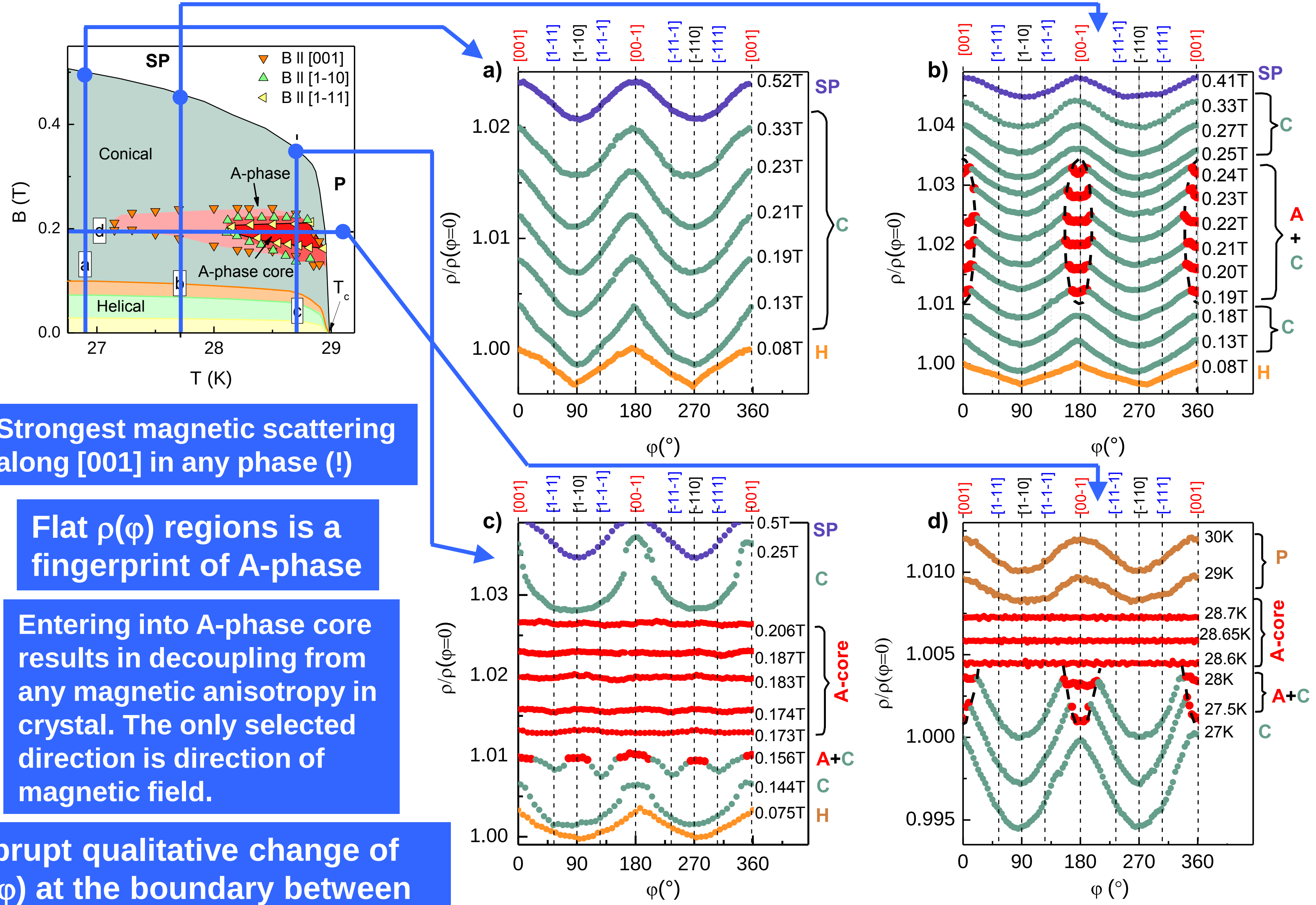


Good agreement with magnetic measurements.

Area, which is common for B II [001], BII[110], BII[111] = A-phase core

Resistivity angular dependences along sections a-d ??

Angular dependences along different sections.



Strongest magnetic scattering along [001] in any phase (!)

Flat ρ(φ) regions is a fingerprint of A-phase

Entering into A-phase core results in decoupling from any magnetic anisotropy in crystal. The only selected direction is direction of magnetic field.

Abrupt qualitative change of ρ(φ) at the boundary between the A-phase and A-phase core.

Magnetic transition between the A-phase and A-phase core.

Q: Is A-phase core a special magnetic phase different from the rest of A-phase?

A1: No. All what you see in angular dependences is nothing but anisotropic phase boundaries.

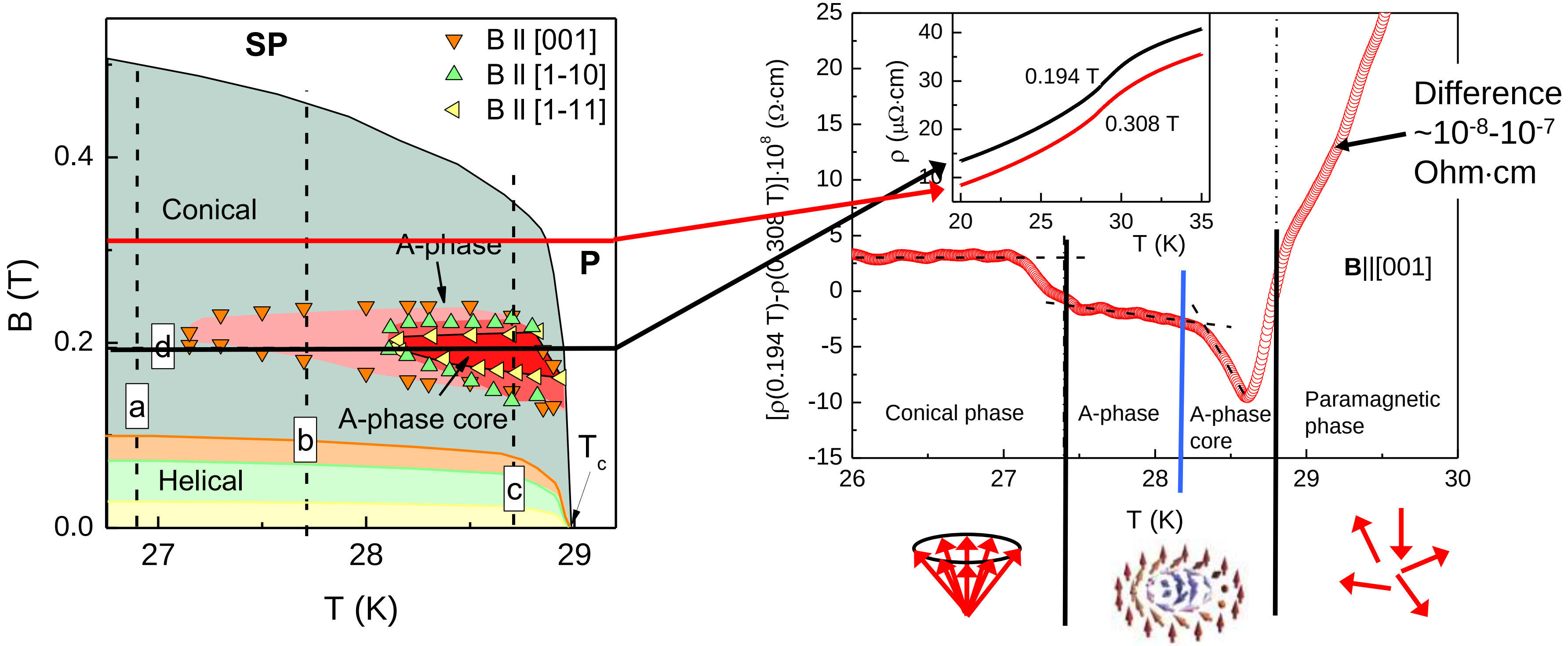
A2: Yes.

In the case of A1 there is no boundary between A-phase and A-phase core for BII[001].

In the case of A2 the boundary between A-phase and A-phase core for BII[001] must exist.

Experimentum crucis:

Magnetic scattering suggests magnetic transition between A-phase and A-phase core!



Conclusions and comments.

Conclusions:

Magnetic transition inside the A-phase is revealed by precise magnetoresistance measurements.

A-phase core is decoupled from any magnetic anisotropy in crystal. Most likely it is analogue of Abrikosov vortex state in superconductor, which is constructed from condensated individual vortexes (skyrmions as quasiparticles, SL1).

Outer part of the A-phase is strongly coupled to magnetic anisotropies (phase boundaries are anisotropic) and may be understood as triple-q structure (complicated anisotropic magnetic phase, SL2), which may be metastable.

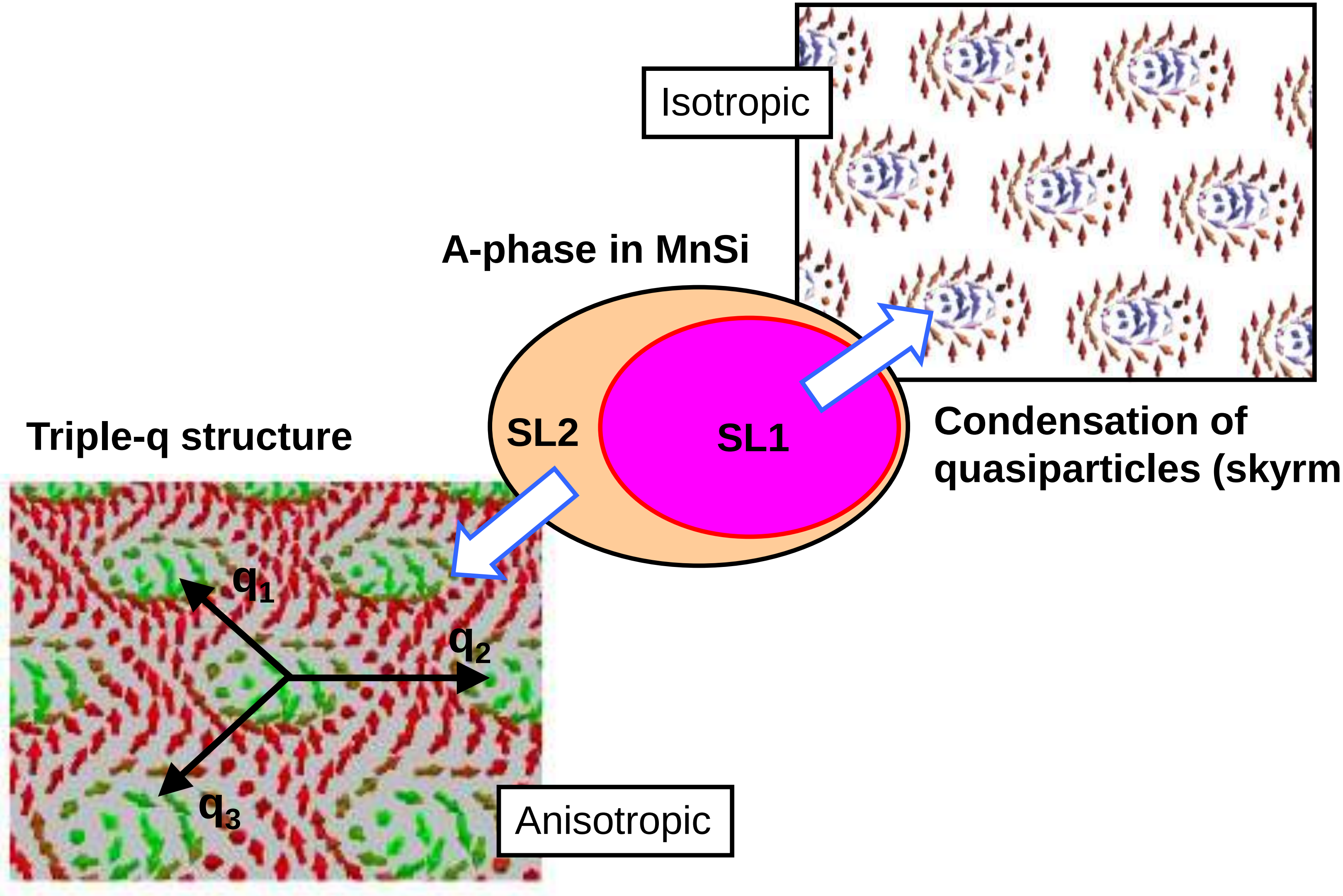
Comments:

Grigoriev problem: Abrikosov-type vortex state is unable to melt into individual skyrmions as long as it is surrounded by another skyrmion-like phase, which is unable to decay into separate quasiparticles.

Theory missed 2D magnetic transition between SL1 and SL2.

Stability problem: Current conclusions about skyrmions stability/metastability are not grounded. Besides cone and paramagnetic phases the stability of SL1 should be considered with respect to SL2 (anisotropic triple-q phase).

Conclusions and comments.



Abrikosov-type vortex phase

Isotropic

A-phase in MnSi

Condensation of quasiparticles (skyrmions)

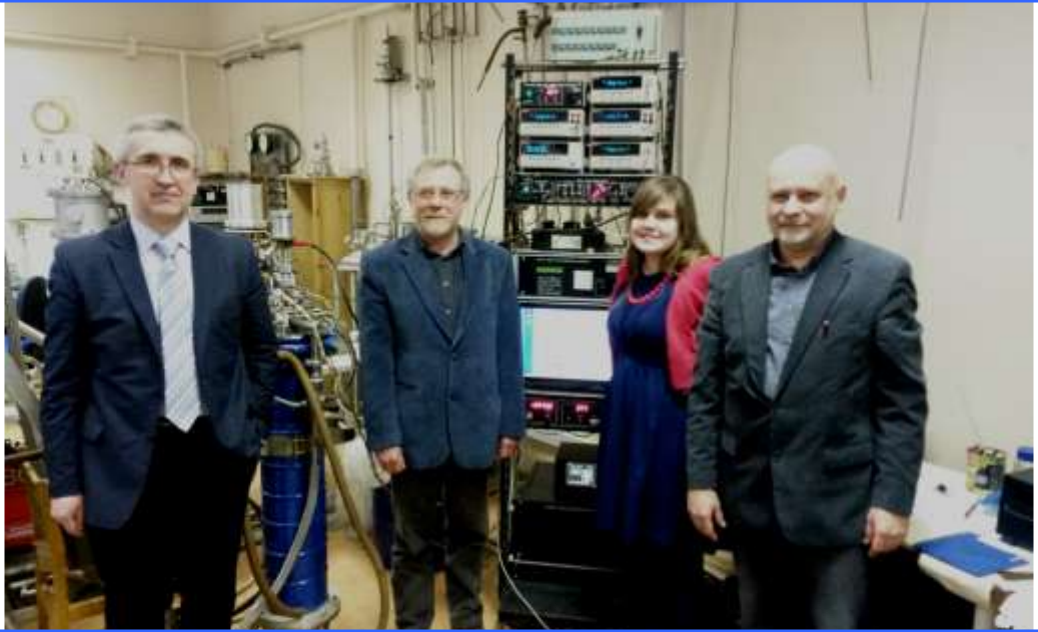
Triple-q structure

Anisotropic

Skyrmion-like complicated magnetic phase

Acknowledgements.

Special thanks to my colleagues Inna Lobanova, Vladimir Glushkov and Nickolay Sluchanko



Thank you for your attention!

We are grateful to:

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