International Workshop

“Dzyaloshinskii-Moriya Interaction and Exotic Spin Structures ”

National Research Centre «Kurchatov Institute»

Petersburg Nuclear Physics Institute

28th May-1th June 2013

Veliky Novgorod, Russia

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Programme

Tuesday, May 28, 2013		
8.00 – 13.30	**Transfer from St-Petersburg to Veliky Novgorod, Check in at the hotel, Registration, Lunch**	
14.00 - 14.05	**Opening ceremony**	
	Session 1. Crystal structure and magnetism in cubic ferromagnets without center of symmetry. Chairman: **Dr. Sergey V. Demishev**	
14.05 – 14.30	**Dmitry Chernyshov** Swiss-Norvegian Beam Lines at ESRF, Grenoble, France	«Structural chirality in MnSi and similar compounds»
14.30 – 14.50	**Sergey Grigoriev** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Spin chirality of transition metal monogermanides»

Session 2. Critical spin fluctuations at the phase transition of MnSi-like compounds.
Chairman: **Dr. Sergey V. Grigoriev**

14.50 – 15.20	**Jonas Kindervater** Technische Universität München, Munich, Germany	«Fluctuation-induced first-order transition in chiral magnets»
15.20 – 15.40	**Evgeny Altynbayev** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Critical scattering in MnGe and Fe-doped compounds»
15.40 -16.00	**Coffee break**	
16.00 – 16.40	**Alla Petrova** Institute for High Pressure Physics of RAS, Troitsk, Russia	«High pressure studies of MnSi»
16.40 – 17.20	**Sergey Demishev** A.M. Prokhorov General Physics Institute, Moscow, Russia	«Magnetic scattering, spin fluctuations and quantum criticality in $Mn_{1-x}Fe_xSi$ solid solutions»
17.20 – 17.40	**Evgeny V. Moskvin** Petersburg Nuclear Physics Institute, Gatchina, Russia	«MnFeSi – when and why the thermal transition changes to quantum?»
17.40 – 18.00	**Vladimir Sidorov** Institute for High Pressure Physics of RAS, Troitsk, Russia	«Pressure effect on the magnetic susceptibility and specific heat of Cu_2OSeO_3 helimagnets»
19.00	**Welcome party**	

Wednesday, May 29, 2013

Session 3. Ferromagnets without center of symmetry in the magnetic field.
Chairman: **Dr. Vladimir Dmitrienko**

9.00 – 9.30	**Andreas Bauer** Technische Universität München, Munich, Germany	«The crystal growth and the magnetic phase diagrams of the B20 compounds»
9.30 – 10.00	**Yoshihiko Togawa** Osaka Prefecture University, Osaka, Japan	«Chiral Soliton Lattice in monoaxial $CrNb_3S_6$ single crystal»
10.00 – 10.20	**Sven-Arne Siegfried** Helmholtz-Zentrum Geesthacht, Munich, Germany	«Small-angle neutron diffraction in transition metal monogermanides $Mn_{1-x}Fe_xGe$ in magnetic field»
10.20 – 10.40	**Olga Makarova** NRC "Kurchatov Institute", Moscow, Russia	«Neutron scattering diffraction on MnGe powder sample»
10.40 – 11.00	**Fedor Mushenok** Institute of Problems of Chemical Physics, Chernogolovka, Russia	«Ferromagnetic resonance in a helimagnet $Cr_{1/3}NbS_2$»
11.00 -11.20	**Coffee break**	
11.20 – 12.30	**Poster session**	
12.30 – 14.00	**Lunch**	

	Session 4. Thin films of cubic ferromagnets without center of symmetry Chairman: **Dr. Ulrich Roessler**	
14.00 – 14.20	**Sergey Maleyev** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Ultra thin layers with Dzyaloshinskii–Moriya interaction. Magnetic structure and spin-waves»
14.20 - 14.50	**Ted Monchesky** Dalhousie University, Halifax, Canada	«Chiral magnetic states in thin MnSi films»
14.50 – 15.20	**Nicholas Porter** University of Leeds, Leeds, England	«Topological Hall effect in epitaxially-strained $Co_xFe_{1-x}Si$ thin films»
15.20 – 15.40	**Josefin Engelke** Institute for Physics of Condensed Matter, Braunschweig, Germany	«Magnetoresistance of the MnSi thin films»
15.40 -16.00	**Coffee break**	

	Session 5. Antiferromagnets without center of symmetry Chairman: **Dr. Dmitry Yu. Chernyshov**	
16.00 – 16.30	**Vladimir Dmitrienko** A.V.Shubnikov Institute of Crystallography RAS, Moscow, Russia	«Exploring the sense of the Dzyaloshinskii—Moriya vector in canted antiferromagnets»
16.30 – 16.50	**Igor Zobkalo** Petersburg Nuclear Physics Institute, Gatchina, Russia	«On the DMI in multiferroics RMn_2O_5»
16.50 – 17.10	**Viacheslav Chizhikov** A.V.Shubnikov Institute of Crystallography, Russia	«Local spin canting in cubic helimagnetics MnSi and Cu_2OSeO_3»
17.10 – 17.30	**Anatoly Tsvyashchenko** Vereshchagin Institute of High Pressure Physics, Troitsk, Russia	«Antiferromagnetic Helical Spin Order Induced the Charge-Density-Wave in Cubic High Pressure Phase $TbGe_{2.85}$»
17.30	**Excursion: The Kremlin, St. Sophia Cathedral, Yaroslav's Courtyard**	

Thursday, May 30, 2013

Session 6, Part I. Exotic spin structures (skyrmions) in the feromagnets with DM interaction.
Chairman: **Dr. Alexander S. Ovchinnikov**

9.00 – 9.40	**Ulrich Roessler** IFW Dresden, Dresden, Germany	«Solitonic states and mesophases in acentric magnets and beyond»
9.40 – 10.00	**Andrey Leonov** University of Groningen, Groningen, The Netehrlands	«Multiple-q states in classical triangular-lattice Heisenberg antiferro- magnet with frustrated interactions»
10.00 – 10.20	**Philipp Rybakov** Institute of Metal Physics, Ural div. of RAS, Yekaterinburg, Russia	«Why do skyrmions exist in nanolayers of cubic helimagnets? Theory of confined chiral modulations»
10.20 – 10.50	**Sergey Maleyev** Prof. Dr., Petersburg Nuclear Physics Institute, Gatchina, Russia	«Bose-Einstain magnon condensation in helical magnets and A-phase problem»
10.50 – 11.10	**Coffee break**	

Session 6, Part II. Exotic spin structures (skyrmions) in the feromagnets with DM interaction.
Chairman: **Dr. Alexander S. Ovchinnikov**

11.10 – 11.30	**Oleg Janson** IFW Dresden, Dresden, Germany	« ab initio calculations on Cu_2OSeO_3 including calculations of the Dzyaloshinskii-Moriya interactions»
11.30 – 11.50	**Alexander A. Tsirlin** National Institute of Chemical Physics and Biophysics, Tallinn, Estonia	«ab initio evaluation of Dzyaloshinsky-Moriya interactions in magnetic insulators»
11.50 – 12.10	**Sergey Grigoriev** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Hexagonal spin structure of A-phase in MnSi: densely packed skyrmion quasiparticles vs two-dimensional spin superlattice»
12.10 – 12.30	**Nadya Potapova** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Critical helix fluctuations and A-phase in MnSi»
12.30 – 14.00	**Lunch**	

Session 7. Spin current and Hall effect in cubic ferromagnets without center of symmetry.
Chairman: **Dr. Ted Monchesky**

14.00 – 14.40	**Alexander S. Ovchinnikov** Ural Federal University, Ekaterinburg, Russia	«Coherent sliding dynamics and spin motive force driven by crossed magnetic fields in a chiral helimagnet»
14.40 – 15.00	**Vladimir E. Sinitsyn** Ural Federal University, Ekaterinburg, Russia	«Numerical simulation of dynamics of a chiral helimagnet in external magnetic fields»
15.00 – 15.20	**Stefan Buhrandt** Institute for Theoretical Physics, University of Cologne, Cologne, Germany	«Unwinding of a skyrmion lattice by magnetic monopoles»
15.20 – 15.40	**Coffee break**	
15.40 – 16.20	**Markus Garst** Institut fur Theoretische Physik, Koln, Germany	«Emergent electrodynamics of skyrmions in a chiral magnet»
16.20 – 16.40	**Andreas Bauer** Technische Universität München, Munich, Germany	«The evolution of the topological Hall effect in MnSi as a function of pressure»
16.40 – 17.00	**Aristov Dmitry** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Peculiarities of magnon spectrum in planar ferromagnets with a skyrmion»
17.30	**Trip aboard a cruise ship to «Rurikovo Gorodische»**	

Friday, May 31, 2013		
	Session 8. DM interaction in nanostructures at the surfaces and interfaces Chairman: **Dr. Markus Garst**	
9.00 – 9.30	**Nikolai Kiselev** Forschungszentrum Jülich, Jülich, Germany	«Magnetic nano-skyrmions and phase transitions in iron monolayer on Ir(111)»
9.30 – 10.00	**Bertrand Dupe** Christian-Abrechts-Universitaet, Kiel, Germany	«First principle study of topologically nontrivial spin structures at surfaces»
10.00 – 10.30	**Dieter Lott** Helmholtz-Zentrum Geesthacht, Geesthacht , Germany	«Chirality in Rare-Earth Multilayer»
10.30 – 10.45	**Vlad Tarnavich** Petersburg Nuclear Physics Institute, Gatchina, Russia	«Study of filed induced chirality in helix structure Ho/Y myltilayers»
10.45 – 11.05	**Coffee break**	

	Session 9. Frustration in the magnetic nanostructures Chairman: **Dr. Dieter Lott**	
11.05– 11.40	**Andrey Fraerman** Institute for physics of microstructures RAS, Nizhniy Novgorod, Russia	«Noncollinear states in lattices of magnetic dipoles»
11.40 – 12.00	**Victor Mironov** Institute for physics of microstructures RAS, Nizhniy Novgorod, Russia	«Magnetic states and ferromagnetic resonance in geometrically frustrated multilayer artificial spin ice on triangular gratings»
12.00 – 12.20	**Alexander Mistonov** Saint Petersburg State University, St.Petersburg, Russia	«The «ice-rule» and magnetization in the inverse opal-like structure»
12.20 – 12.40	**Victor Mironov** Institute for physics of microstructures RAS, Nizhniy Novgorod, Russia	«Antivortex state in cross-like nanomagnets»
12.40 – 13.00	**Konstantin Zvezdin** A.M.Prokhorov General Physics Institute, RAS, Moscow, Russia	«Spin-orbit torques for efficient domain-wall motion»
13.00 – 14.00	**Lunch**	
15.00 – 19.00	**Excursion: Museum of Wooden Architecture "Vitoslavlitsy"**	
19.00 – 22.00	**Closure of conference and Conference dinner**	

POSTERS

- Surface- and defect-induced Dzyaloshinskii-Moriya interactions: influence on vortex states in magnetic nanodots
  Anna. B. Butenko

- Hall effect of MnSi thin films
  J. Engelke

- Fluctuation-driven first-order transition in the chiral magnet MnSi
  Markus Garst

- Long-range and short-range magnetic order in a quantum critical model of $Mn_{1-x}Fe_xSi$
  T.V.Ischenko

- Microscopic modeling of the S=1/2 Heisenberg ferrimagnet Cu_2OSeO_3
  O. Janson

- Magnetoresistance and exchange interaction in $Mn_{1-x}Fe_xSi$
  I.I. Lobanova

- Coherent sliding dynamics and spin motive force driven by crossed magnetic fields in a chiral helimagnet
  A.S. Ovchinnikov

- Spin polarization in strained epitaxial $Fe_{1-x}Co_xSi$ thin films
  P. Sinha

Session 1. Crystal structure and magnetism in cubic ferromagnets without center of symmetry.

Chairman: Dr. Sergey V. Demishev

Spin chirality of $Mn_{1-x}Fe_xGe$ compounds

S.V. Grigoriev[1,2], N.M. Potapova[1], S.-A. Siegfried[3], V. A. Dyadkin[4,1], E. V. Moskvin[1,2], V. Dmitriev[4], D. Menzel[5], C. D. Dewhurst[6], D. Chernyshov[4], R.A. Sadykov[7,8], L.N. Fomicheva[8] and A.V. Tsvyashchenko[8]

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The crystal structures of MnSi and doped monosilicides of Mn and Fe ($Mn_{1-x}Fe_xSi$, $Mn_{1-x}Co_xSi$ and $Fe_{1-x}Co_xSi$) have the same B20 type cubic noncentrosymmetric crystallographic structure described by the chiral $P2_13$ space group. It is known that the Dzyaloshinskii-Moriya (DM) interaction stabilizes the spiral spin structure in these systems below T_c. Systematic studies have shown that the sense of the structural chirality (left or right) rigorously determines the sense of the magnetic chirality via the sign of the DM interaction. However, for Mn based compounds ($Mn_{1-x}Fe_xSi$ and $Mn_{1-x}Co_xSi$) the crystalline and magnetic chiralities have the same sense, while for the Fe based ones ($Fe_{1-x}Co_xSi$) the chiralities are opposite to each other. One can conclude that the two types of the compounds, Mn- and Fe-based, posses different signs of the DM interaction for the crystals of the same chirality. An intriguing experiment for proof of this hypothesis would be the change of the chirality sense in the $Mn_{1-x}Fe_xSi$ family by changing the Mn to Fe ratio. Unfortunately, the $Mn_{1-x}Fe_xSi$ family shows the spin ordering only in a narrow range of $x \in [0 - 0.15]$, and further Fe-doping leads to magnetic disorder.

A good candidate to follow the change of the magnetic chirality is the $Mn_{1-x}Fe_xGe$ family with B20 structure. We have synthesized the $Mn_{1-x}Fe_xGe$ compounds (with x running from 0.0 to 1.0) by the high pressure method [1]. Samples were in a polycrystalline powder form with a crystallite size larger than a micron. Magnetic susceptibility measurements have shown that the compounds $Mn_{1-x}Fe_xGe$ are magnetically ordered through the whole range of concentrations $x \in [0 - 1]$. Small-angle neutron diffraction reveals the helical nature of the spin structure with a wavevector, which changes from its maximum ($k = 2.3$ nm^{-1}) for pure MnGe, through its minimum ($k = 0$) at $x_c \approx 0.75$ to the value of $k = 0.09$ nm^{-1} for pure FeGe. The macroscopic magnetic measurements confirm the ferromagnetic nature of the compound with $x = x_c$. The observed transformation of the helix structure to the ferromagnet at $x = x_c$ is explained by different signs of chirality for the compounds with $x > x_c$ and $x < x_c$. We used X-ray diffraction and polarized neutron scattering to evaluate the crystallographic chirality Γ_c and the magnetic chirality γ_m of the FeGe single crystals. Similar to previous observations for FeSi based compounds, FeGe demonstrates left-(right-) handed crystalline chirality acompained by right- (left-) handedness of the magnetic helix ($\Gamma_c\gamma_m = -1$). Referring to the change of sign of the DM interaction in the $Mn_{1-x}Fe_xGe$ compounds, MnGe crystals have the same signs for crystalline and magnetic chirality in accordance to the MnSi based compounds ($\Gamma_c\gamma_m = 1$). One can conclude that the sign of DMI depends on 3d element occupying metal site [2].

References

[1] A. Tsvyashchenko, *J. Less Common Metals* **99**, L9 (1984)

[2] S. V. Grigoriev, N. M. Potapova, S.-A. Siegfried, V. A. Dyadkin, E. V. Moskvin, V. Dmitriev, D. Menzel, C. D. Dewhurst, D. Chernyshov, R. A. Sadykov, L. N. Fomicheva, and A. V. Tsvyashchenko, *Phys. Rev. Lett.*, accepted (2013)

Session 2. Critical spin fluctuations at the phase transition of MnSi-like compounds.

Chairman: Dr. Sergey V. Grigoriev

Fluctuation induced first-order transition in chiral helimagnets

J. Kindervater[1], W. Häußler[21], M. Garst[3], A. Bauer[1], M. Janoschek[4], H. Berger[5], S. Mühlbauer[2], U. Gasser[6], C. Pfleiderer[1] and P. Böni[1]

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Generic aspects of the magnetic phase transition in chiral magnets have recently been discussed controversially. On the one hand, the unusual signatures observed just above the transition temperature have been attributed to an intermediate skyrmion liquid [1, 2] or a magnetic blue phase [3]. On the other hand, they have been interpreted in terms of chiral paramagnons [4] that eventually drive the transition weakly first order [5, 6]. Indeed, a detailed study combining results from thermodynamic and neutron scattering experiments has revealed that the paramagnetic to helimagnetic transition in MnSi is a fluctuation-induced first order transition belonging to the Brazovskii class [6].

We report results from small-angle neutron diffraction from the conducting intermetallic MnSi and the insulating multiferroic Cu_2OSeO_3. Our comparative study demonstrates the universal aspects of the Brazovskii transition in both compounds in zero and applied magnetic fields.

References

[1] Rößler et al., *Nature* **442**, (2006)
[2] Pappas et al., *PRL* **102**, (2009)
[3] Hamann et al. *PRL* **107**, 037207 (2011)
[4] Grigoriev et al., *PRB* **72**, (2005)
[5] Bak and Jensen, *Journal of Physics* **C 13**, (1980)
[6] Brasovskii, *Zh. Eksp. Teor. Fiz.* **68**, (1975)

Magnetic structure of MnGe in a wide temperature range

E. V. Altynbayev[1,2], S.-A. Siegfried[3], N.M. Potapova[1], V. A. Dyadkin[1,4], E. V. Moskvin[1,2], D. Menzel[5], Ch. Dewhurst[6], R.A. Sadykov[7,8], L.N. Fomicheva[8], A.V. Tsvyashchenko[8], S. V. Grigoriev[1,2]

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The cubic B20-type compound MnGe orders below T_C in a one-handed spin helical structure with a small propagation vector $k \approx 2.2$ nm^{-1}. The small-angle neutron scattering (SANS) experiments are performed to study details of the temperature evolution of the spin structure above and below T_C.

Polycrystalline MnGe sample has been synthesized by high pressure method [1]. SANS measurements are carried out at instrument D11 at the Institute Laue-Langevin (ILL). Neutrons with a mean wavelength of $\lambda = 0.6$ nm were used. The Sample-Detector distance of 2 m was used to cover scattering vectors Q from 0.1 nm^{-1} to 4.0 nm^{-1}. The scattering intensity is measured upon zero field cooling from the paramagnetic state at T = 300 K to ordered state at T = 5 K.

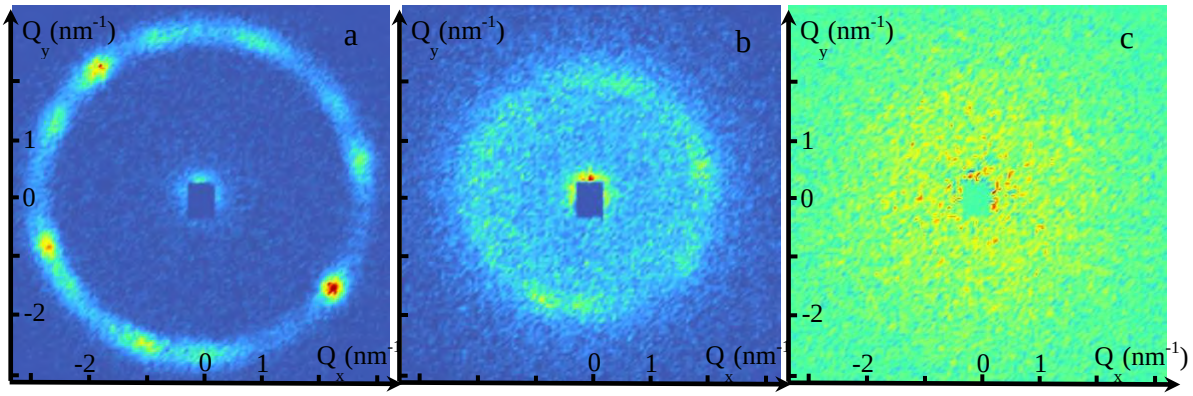

Fig.1 *maps of the SANS intensity for MnGe at (a) T=20 K, (b) T=135 K and (c) T=220 K.*

Figure 1 shows examples of the magnetic scattering (maps of the SANS intensity) for MnGe compound at (a) T=20 K, (b) T=135 K and (c) T=220 K. The temperature evolution of the magnetic structure of MnGe sample is found to be different at different temperature ranges (Fig.2). In the below T_{C1} = 140(2) K a typical powder pattern can be observed, i.e. the presence of a ring of intensity which indicates the coexistence of different spiral domains in the sample with randomly oriented helix wavevectors k. This reflection is well described by Voigt

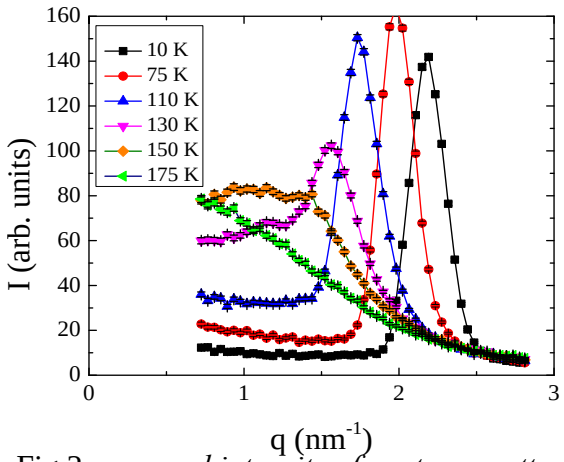

Fig.2 *averaged intensity of neutron scattering extracted from the maps at different temperatures*

function. The Bragg peak parameters (integral intensity, width and position) were extracted from the measurements.

The integral intensity increases weakly in 0-100 K temperature range (Fig. 3a). The value of the wavevector k at low temperature of 10 K is equal to 2.2 nm^{-1}. It decreases slowly upon temperature increase in this range (Fig.3b) and the width of the reflection remains almost constant. Additional scattering can be observed upon temperature increase. This scattering is well described by the convolution of Heaviside (step-like) function and Voigt function with the step at q equal to k. We ascribe this scattering to the spin excitations. At T_{C1} intensity of the peak becomes smaller then intensity of step-like function and disappears with further temperature increase at $T_{C2} \approx 180$ K. At T = 200 K scattering is well described by single Gaussian function with center position at q = 0 and width which increases with temperature (Fig. 3b). Its intensity decreases smoothly upon further temperature increase. The critical temperatures of T_{C1}, T_{C2} coincide with the inflection points of the temperature dependence of magnetic susceptibility $\chi(T)$ for this compound (Fig. 3c)

This work is supported by the German-Russian Interdisciplinary Science Center (G-RISC) founded by the German Federal Foreign Office via the German Academic Exchange Service (DAAD).

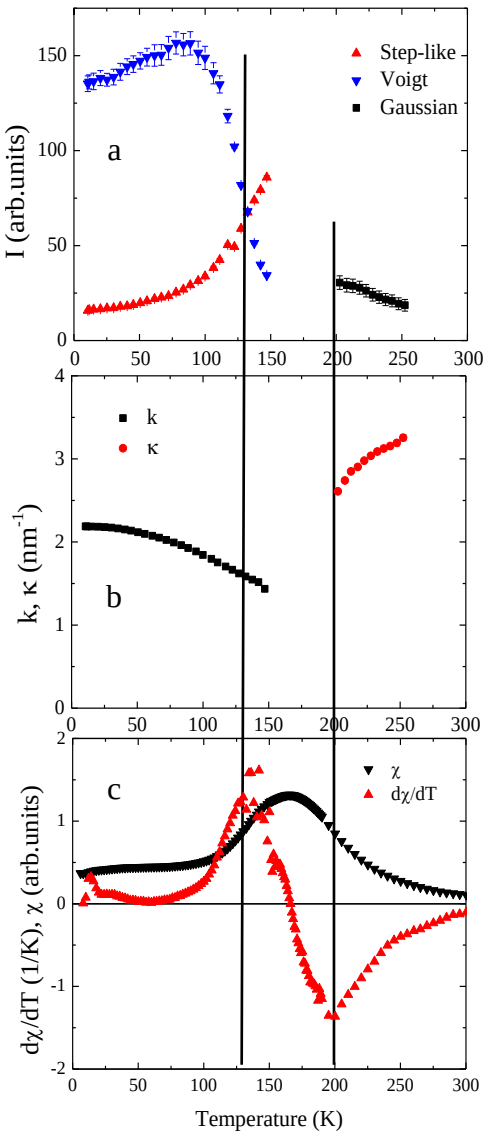

Fig.3 *fitting function parameters and derivative of magnetic susceptibility as function of temperature*

References

[1] A. Tsvyashchenko, et al., *Journal of the Less Common Metals* ***99***, 2, L9 (1984)

High pressure studies of MnSi

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A series of resistivity measurements was performed on a MnSi single crystal at high pressures, created by a piston-cylinder device with a liquid pressure medium [1]. The form of the resistivity curve at ambient pressure clearly indicates a first-order nature of the magnetic phase transition in MnSi. Application of high pressure rapidly degrades the first-order features of the phase transition (Fig. 1). The temperature derivative of resistivity demonstrates two notable features of the phase transition that disappear on increasing pressure: a sharp peak marking the first-order phase transition and a shallow maximum situated slightly above the critical temperature and pointing to prominent helical fluctuations. The current experimental data rule out any strong first-order phase transition in MnSi at high pressures and low temperatures, which would prevent development of a quantum critical region. On the contrary, there should exist true quantum critical phenomena in MnSi at high pressures because a weak first-order transition, if it survives at high pressures to the lowest temperatures, should not suppress the entire quantum critical region.

The sharp peaks and shallow shoulders in the temperature derivatives of resistivity of MnSi, which indicate a first-order phase transition and a helical fluctuation domain, respectively, disappear simultaneously at 16 K and 1 GPa (Fig. 1, 2). This may imply the existence of a tricritical point on the phase transition line (Fig. 2). On the other hand, it may mean that the first-order phase transition, being smeared by nonhydrostatic stresses in a frozen liquid, continues to the lowest temperatures. Note that in fact the imaginable conflict expected earlier between the volume discontinuity at ambient pressure and the high-pressure low-temperature volume anomaly does not exist at all because these discontinuities are related to different physical phenomena. In either case, the present experimental data do not support the idea of a strong first-order transition in MnSi at $T \rightarrow 0$, which would prevent development of the quantum critical region.

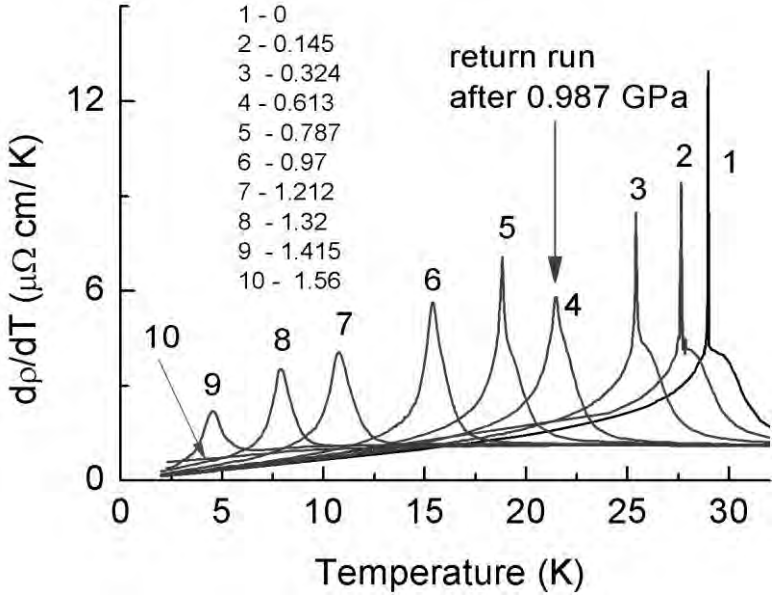

Fig. 1 *Temperature derivatives of resistivity at the phase transitions in MnSi at different pressures.*

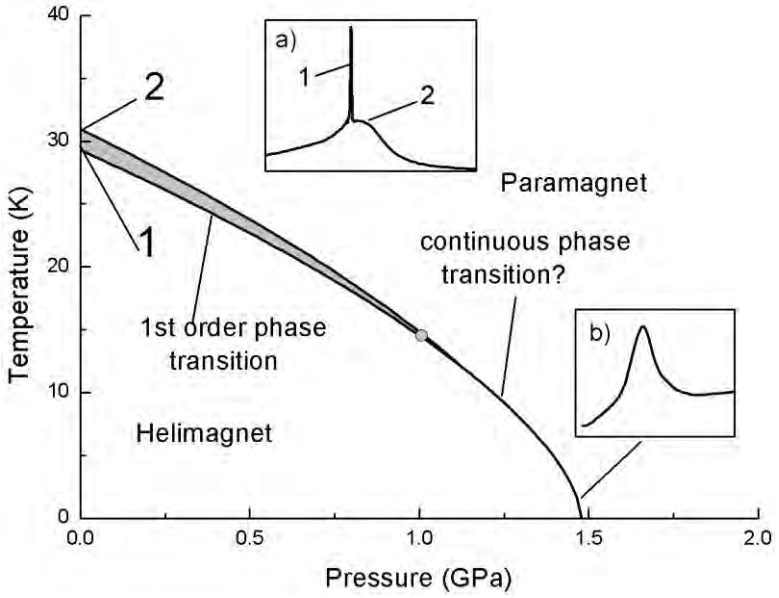

Fig. 2. *Tentative phase diagram of MnSi at high pressure. The grey region shows the helical fluctuation domain, disappearing at a pressure ~1GPa. The grey circle could be a critical point, if the phase transition at pressures >1GPa is truly continuous. a) and b) illustrate variations of the form dρ/dT with pressure.*

This research is supported by the Russian Foundation for Basic Research (12-02-00376-a), Program of the Physics Department of RAS on Strongly Correlated Systems, and Program of the Presidium of RAS on Physics of Strongly Compressed Matter.

References

[1] A.E. Petrova and S.M. Stishov, *Phys. Rev. B* **86**, 174407 (2012)

Magnetic scattering, spin fluctuations and quantum criticality in $Mn_{1-x}Fe_xSi$ solid solutions

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The *T-x* magnetic phase diagram of $Mn_{1-x}Fe_xSi$ solid solutions is probed by magnetic susceptibility, magnetization, resistivity, magnetoresistance and magnetic resonance measurements. It is found that substitution of manganese by iron leads to enhancement of spin fluctuations and induces transformation of the magnetic state corresponding to Heisenberg-type localized magnetic moments (x =0, MnSi) into itinerant magnet (x =1, FeSi). The boundary, which limits phase with short-range magnetic order (chiral spin liquid, CSL), is defined experimentally and described analytically within suggested simple model accounting both classical and quantum magnetic fluctuations together with effects of disorder. Probing of the CSL state in magnetoresistance experiments followed by analysis within Yosida model [1] allowed establishing the enhancement of the CSL region stability in magnetic field. It is shown that $Mn_{1-x}Fe_xSi$ system undergoes a sequence of quantum phase transitions. The first "underlying" quantum critical (QC) point $x^* \sim 0.11$ corresponding to disappearance of the long-range magnetic order is masked by CSL short-range order phase. However, this quantum phase transition manifests itself at finite temperatures by crossover between classical and quantum fluctuations, which is predicted and observed in the paramagnetic phase as a peculiarity of magnetic scattering. The second QC point $x_c \sim 0.24$ may have topological nature and corresponds to percolation threshold in magnetic subsystem of $Mn_{1-x}Fe_xSi$. Above x_c the short-range ordered CSL phase is suppressed and magnetic subsystem becomes separated into spin clusters, which results in observation of the disorder-driven QC Griffiths-type phase characterized by anomalously divergent magnetic susceptibility $\chi \sim 1/T^{\xi}$ with the exponents $\xi \sim 0.5\text{-}0.6$.

This work was supported by Programme of Russian Academy of Sciences "Strongly correlated electrons" and by RFBR grant 13-02-00160.

References

[1] 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, *Physical Review B* **85**, 045131 (2012)

Approaching quantum criticality in $Mn_{1-x}Fe_xSi$: SANS Pol study

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We studied the critical spin fluctuations and spin structure in $Mn_{1-x}Fe_xSi$, compounds in the vicinity of the quantum phase transition at $x_c \approx 0.15$. Compounds with $x = 0.1, 0.12, 0.145, 0.15, 0.16$ were studied by ac susceptibility and polarized neutron small-angle scattering. In accord with our previous study [1] the compound with $x = 0.10$ undergoes the transition from the paramagnetic to helimagnetic phase at $T_C \approx 7$ K through the well distinguishable crossovers: (I) from paramagnetic to partially chiral and (II) from partially chiral to fully chiral fluctuating state. The compounds with $x = 0.145$ and 0.15 show enhancement of the criticality with lowering temperature to $T = 1.7$ K. We obtained temperature and magnetic field dependencies of the inverse correlation length, κ, susceptibility, χ and magnetic structure wave vector, $\mathbf{k}_0$, for the above-mentioned compounds. No spin ordering was observed for the compounds with $x > x_c$. Extrapolation to $T = 0$ verifies our assumption of their closeness to the quantum phase transition. Compound with $x = 0.16$ does not exhibit any long-range order or fluctuations down to the lowest measured T. It clearly means that this concentration is already above the critical value x_c of quantum phase transition.

References

[1] Sergey V. Grigoriev, Evgeny V. Moskvin, Vadim A. Dyadkin, Daniel Lamago, Thomas Wolf, Helmut Eckerlebe, and Sergey V. Maleyev, *Phys. Rev. B* **83**, 224411 (2011)

Pressure effect on the magnetic susceptibility and specific heat of Cu_2OSeO_3 helimagnet

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The family of compounds MnSi, $Mn_{1-x}Fe_xSi$, FeGe having a cubic B20-type (space group $P2_13$) crystal structure order magnetically at low temperatures in a spin helix structure with a long period of helix. The appearance of this spin helix structure is due to Dzyaloshinskii-Moriya interaction (DMI) related with the lack of inversion symmetry of a crystal lattice, in addition to the main ferromagnetic spin exchange. Recently a compound Cu_2OSeO_3 possessing a cubic non-centrosymmetric $P2_13$ crystal structure was found to have a magnetic structure and T-H magnetic diagram similar to those of MnSi [1]. We have studied the magnetic transition in this material by means of magnetic ac-susceptibility and ac-calorimetry at nearly hydrostatic pressure up to 6 GPa.

Single crystals of Cu_2OSeO_3 were grown by a gas transport technique in 610–550°C temperature gradient using 2:1 CuO/SeO_2 mixture and $CuCl_2 \cdot 2H_2O$ as a transport agent. High pressures were created in a small Teflon capsule filled with liquid and inserted in a miniature toroid-type clamped device [2]. The specific heat C(T) at high pressure was measured by ac-calorimetry technique as described earlier [3]. The coil system for magnetic ac-susceptibility measurements $\chi(T)$ was arranged inside the Teflon capsule. Pressure was measured by superconducting transition temperature of Pb located near Cu_2OSeO_3 sample.

The temperature of the transition to the spin helix structure (T_C = 57.5 K at ambient pressure) increases nearly linearly at high pressure up to 6 GPa with the initial slope 3 K/GPa (Fig.1). This is in good agreement with earlier measurements of ac-susceptibility up to 2 GPa [4]. The dependences $\chi(T)$ and C(T) near T_C at ambient pressure are depicted in Fig.2. $\chi(T)$ has a sharp drop at T_C and an inflection point ~1 K above T_C. The midpoint of a specific heat anomaly near T_C corresponds to this inflection point of $\chi(T)$ and an additional sharp peak of C(T) corresponds to a sharp drop of $\chi(T)$. The maximum of C(T) is located ~ 0.3 K above T_C. The existence of a sharp peak of C(T) superimposed on a broad one was reported earlier for Cu_2OSeO_3 [1] and for MnSi [5,6].

All these features may be related with the development of the chiral spin fluctuations in Cu_2OSeO_3 near T_C in the spirit of model proposed by Grigoriev et al. [7] for the related system $Mn_{1-x}Fe_xSi$ on the basis of the magnetic ac-susceptibility and SANS measurements. In this case, three vertical lines in Fig.2 (right to left) correspond to the development of partially chiral spin fluctuations, strongly chiral spin fluctuations and the appearance of a static chiral magnetic order. The temperature range ΔT between two peaks of the specific heat corresponds to the region of strong chiral fluctuations. The value of ΔT increases nearly linearly at high pressure for Cu_2OSeO_3 (from ΔT = 0.31 K at P = 0 to ΔT = 0.54 K at 4.6 GPa) in line with the increase of T_C. For MnSi ΔT decreases and vanishes under pressure [8], again in line with the pressure effect on T_C (decrease of T_C). Finally we see a very close similarity between two materials MnSi (metal) and Cu_2OSeO_3 (insulator) which may be of importance for development of theoretical models and for better understanding of role of DMI in chiral systems.

This research was supported by the Russian Foundation for Basic Research (Grants 12-02-00376-a, 12-03-00665-a and 12-03-92604-KO_a), Program of the Physics Department of RAS on Strongly Correlated Systems, and Program of the Presidium of RAS on Physics of Strongly Compressed Matter.

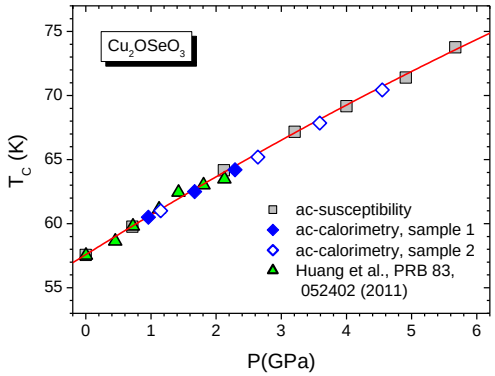

Fig. 1 *The magnetic P-T diagram of Cu_2OSeO_3 based on the magnetic ac-susceptibility (T_C corresponds to a sharp drop of χ(T) in Fig.2) and specific heat (T_C corresponds to a narrow and sharp peak of C(T) in Fig.2).*

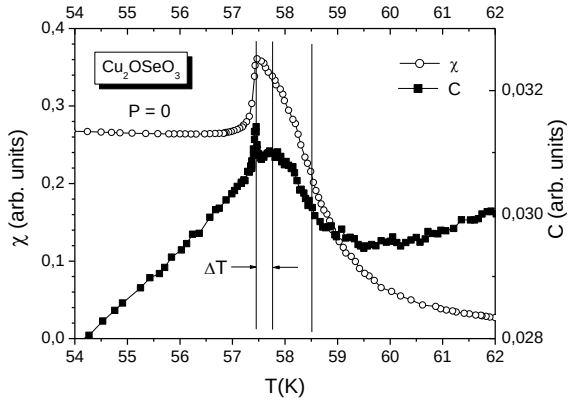

Fig. 2 *The dependences of the magnetic ac-susceptibility χ(T) and specific heat C(T) of Cu_2OSeO_3 in the vicinity of T_C at ambient pressure.*

References

[1] T. Adams, A. Chacon, M. Wagner, A. Bauer, G. Brandl, B. Pedersen, H. Berger, P. Lemmens and C. Pfleiderer, *Phys. Rev. Lett.* ***108***, 237204 (2012)

[2] A.E. Petrova, V.A. Sidorov and S.M. Stishov, *Physica B* ***359-361***, 1463 (2005)

[3] V.A. Sidorov, J.D. Thompson and Z. Fisk, *Journal of Physics: Condensed Matter* ***22***, 406002 (2010)

[4] C.L. Huang, K.F. Tseng, C.C. Chou, S. Mukherjee, J.L. Her, Y.H. Matsuda, K. Kinda, H. Berger and H.D. Yang, *Phys. Rev. B* ***83***, 052402 (2011)

[5] S.M. Stishov, A.E. Petrova, S. Khasanov, G.Kh. Panova, A.A. Shikov, J.C. Lashley, D. Wu and T.A. Lograsso, *Phys. Rev. B* ***76***, 052405 (2007)

[6] S.M. Stishov and A.E. Petrova, *Physics-Uspekhi* ***54***, 1117 (2011)

[7] S.V. Grigoriev, E.V. Moskvin, V.A. Dyadkin, D. Lamago, T. Wolf, H. Eckerlebe and S.V. Maleyev, *Phys. Rev. B* ***83***, 224411 (2011)

[8] A.E. Petrova and S.M. Stishov, *Phys. Rev. B* ***86***, 174407 (2012)

Session 3. Ferromagnets without center of symmetry in the magnetic field.

Chairman: Dr. Vladimir Dmitrienko

The magnetic phase diagram of cubic chiral helimagnets

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We report detailed measurements of the magnetization and the ac susceptibility of the cubic chiral helimagnet MnSi across the entire magnetic phase diagram.[1] In our study we explore the importance of the excitation frequency, excitation amplitude, sample shape, and crystallographic orientation. The susceptibility, *dM/dH*, calculated from the magnetization, is dominated by pronounced maxima at the transition from the helical to the conical and the conical to the skyrmion lattice phase. The maxima in *dM/dH* are not tracked by the ac susceptibility, which in addition varies sensitively with the excitation amplitude and frequency at the transition from the conical to the skyrmion lattice phase. The same differences between *dM/dH* and the ac susceptibility exist for $Mn_{1-x}Fe_xSi$, $Fe_{1-x}Co_xSi$, and Cu_2OSeO_3.

These results are combined with high-precision measurements of the temperature and magnetic field dependence of the specific heat across the magnetic phase diagram of MnSi.[2] Clear anomalies establish the skyrmion lattice unambiguously as a thermodynamic phase. The evolution of the specific heat anomalies, the field dependence of the entropy released at the phase transitions, and the temperature versus field dependence of crossover lines provide striking evidence of a field induced tricritical point. The existence of this tricritical point represents strong support of a helimagnetic Brazovskii transition, i.e., a fluctuation-induced first order transition at zero field.

References

[1] A. Bauer and C. Pfleiderer, *Phys. Rev. B* **85**, 214418 (2012)
[2] A. Bauer, M. Garst, and C. Pfleiderer, *Phys. Rev. Lett. (in press)* (2013)

Chiral Soliton Lattice in monoaxial $CrNb_3S_6$ single crystal

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The concept of chirality, meaning left- or right-handedness, plays an essential role in symmetry properties of nature at all length scales from elementary particles to biological systems. In materials science, chiral materials are found in molecules or crystals with helical structures, which break mirror and inversion symmetries but combine rotational and translational symmetries. Chiral materials frequently exhibit intriguing functionality because electrons distribute themselves along chiral framework of atomic configurations and their rotational and translational motions couple to give specific physical processes.

In magnetic crystals belonging to chiral space group, orbital motions of localized electrons with spin magnetic moments take helical paths in the chiral framework of atoms and mediate coupling of the neighboring spins of electrons via the relativistic spin-orbit interaction called Dzyaloshinskii-Moriya (DM) interaction. This antisymmetric DM exchange competes with ferromagnetic (FM) exchange interaction, which will result in an emergence of chiral magnetic orders and various interesting functions unique to chiral magnets.

In this presentation, we directly present that chiral soliton lattice (CSL) emerges in a monoaxial chiral magnet $CrNb_3S_6$ in small magnetic fields [1] by means of low-temperature Lorenz transmission electron microscopy (TEM) and small-angle electron scattering (SAES) method [2]. Based on detailed analyses in both real and reciprocal space, we clearly demonstrate that CSL develops from chiral helimagnetic structure (CHM) with increasing the spatial period from 48 nm toward infinity in rising magnetic fields perpendicular to the helical axis. Chiral magnetic orders of CSL and CHM do not exhibit any structural dislocation, indicating their high stability and robustness. This is because chiral magnetic orders are macroscopically induced by the uniaxial Dzyaloshinkii-Moriya (DM) exchange interaction that is allowed in $CrNb_3S_6$ hexagonal crystals belonging to noncentrosymmetric chiral space group. Magnetization and interlayer magneto-resistance data in $CrNb_3S_6$ crystals will be discussed in terms of CSL formation [3].

In theoretical viewpoints, CSL would exhibit a variety of interesting functions including spin current induction, nontrivial soliton transport, anomalous topological magneto resistance [4], current-driven collective CSL transport [5] and so on. Present observations of a new state of matter will be the first step to explore novel type of functionalities of CSL for spintronic device applications using chiral magnetic crystals [6].

References

[1] Y. Togawa, T. Koyama, S. Mori, Y. Kousaka, J. Akimitsu, S. Nishihara, K. Inoue, A. S. Ovchinnikov and J. Kishine, *Phys. Rev. Lett.* **108**, 107202 (2012)

[2] Y. Togawa, *Microscopy, in press*; K. Takayanagi, T. Koyama, S. Mori, K. Harada and Y. Togawa, *J. Electron Microscopy* **61**, 401 (2012); T. Koyama, K. Takayanagi, Y. Togawa, S. Mori and K. Harada, *AIP Advances* **2**, 012195 (2012)

[3] Y. Togawa, Y. Kousaka, S. Nishihara, K. Inoue, J. Akimitsu, A. S. Ovchinnikov and J. Kishine, *submitted.*
[4] J. Kishine, I. V. Proskurin and A. S. Ovchinnikov, Phys. Rev. Lett. **107**, 017205 (2011)
[5] J. Kishine, I. G. Bostrem, A. S. Ovchinnikov and VI. E. Sinitsyn, Phys. Rev. B **86**, 214426 (2012)
[6] C. Pappas, Physics **5**, 28 (2012)

Two ground states in mixed $Mn_{1-x}Fe_xGe$ compounds

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The cubic B20 type transition-metal monogermanides belong to the $P2_13$ space group. Pure MnGe and FeGe order in a one-handed helical structure below T_C with a propagation vector of $\mathbf{k} \approx 2.3$ nm^{-1} for MnGe and $\mathbf{k} \approx 0.09$ nm^{-1} for FeGe [1,2,3]. The helicity is introduced by Dzyaloshinskii-Moriya (DM) exchange interaction caused by the non-centrometric arrangement of the magnetic atoms in these compounds [4,5]. The orientation of the spiral is fixed along the principal axes of the cubic structure by Anisotropic Exchange (AE) interaction and cubic anisotropy. Polycrystalline $Mn_{1-x}Fe_xGe$ samples ($x \in [0.0\text{-}1.0]$) have been synthesized by high pressure method [6]. SQUID magnetization measurements were used to establish the magnetic ordering temperature. T_C decreases from x = 0.0 to x = 0.4 from 140 K to 120 K and increases linearly to 278 K for further Fe doping up to x = 1.0.

Small angle neutron scattering (SANS) measurements were carried out at the instruments D11 at the Institute Laue-Langevin (ILL) and the SANS-1 at the Meier-Leibnitz-Zentrum (MLZ). For all field dependent measurements a magnetic field perpendicular to the incoming neutron beam has been used. As shown in fig. 1 the behavior for $Mn_{1-x}Fe_xGe$ with $x \leq 0.4$ is similar to pure MnGe, while for $x > 0.75$ it behaves similar to pure FeGe. The samples with an iron concentration of $0.4 < x < 0.75$ show a deviance additional second state.

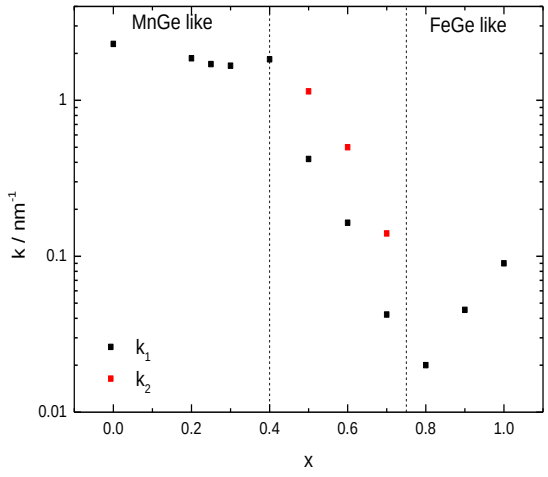

Fig. 1 *Dependence of the helix wavevector $k_{1,2}$ on the concentration x.*

In the following the sample $Mn_{0.4}Fe_{0.6}Ge$ will be discussed in more details. For low temperatures a transition from the ring-like pattern (fig.3a) (which indicates the coexistence of randomly oriented wavevectors **k**) to a spot like pattern with two spots (fig.3b) in magnetic field direction ($\mathbf{k}_1 \parallel \mathbf{H}$) is observed due the reorientation of the wavevectors along the external field direction. The critical field for this reorientation is $H_{C1} \approx 0.15$ T. For further field increasing the

double scattering in field direction disappears and the remaining peak broads (fig.3c). In the field region between $H_{C1} \approx 0.15$ T and $H_{C2} \approx 0.45$ T an intermixed helical state seems to exist. In this range the helical structure oscillates between the two gound states with $\mathbf{k}_1$ and $\mathbf{k}_2$.

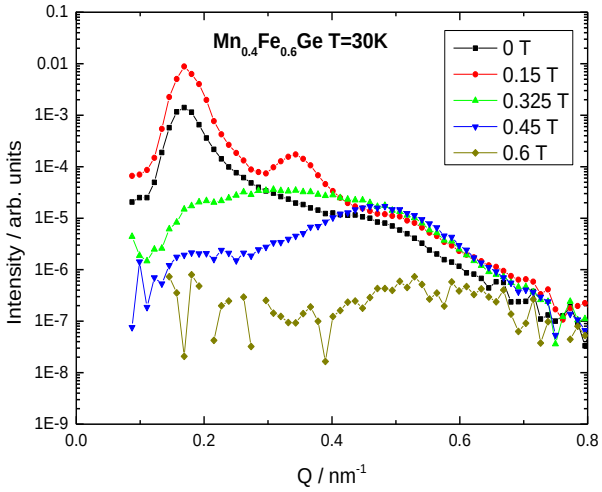

Fig. 2 *Momentum transfer dependence of the SANS intensity at 30 K for magnetic fields between 0 and 0.6 T.*

Above H_{C2} up to $H_{C3} \approx 0.6$ T the broadend peak contracts again to one thin peak (fig.3d) and just one single helix exists with $\mathbf{k}_2$. Finally for fields higher then 0.6 T the helical structures vanishes and the spin structure becomes field aligned.

In conclusion we have observed a non-trivial field evolution of the magnetic structure in the intermixed compound $Mn_{1-x}Fe_xGe$. While for high Fe/Mn concentration the compounds behave like pure FeGe/MnGe, the mean concentration range ($x \in [0.4\text{-}0.75]$) giving rise for a second different magnetic ground state.

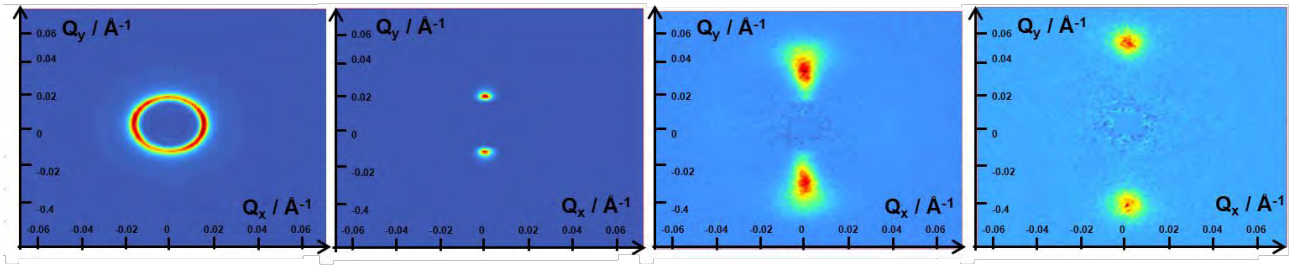

Fig. 3 SANS maps for $Mn_{0.4}Fe_{0.6}Ge$ at 30 K: a) 0T, b) 0.15 T, c) 0.35 T, d)0.5 T

References

[1] N. Kanazawa, et al., *Phys. Rev. Lett.* **106**, 156603 (2011)
[2] O.L. Makarova, et al., *Phys. Rev. B* **85**, 205205 (2012)
[3] B. Lebech, et al., *J. Phys. Condens. Matter* **1**, 6105 (1989)
[4] I. E. Dzyaloshinskii, *Zh. Eksp. Teor. Fiz.* **46**, 1420 (1964)
[5] P. Bak, M.H. Jensen, *J. Phys.* **C13**, L881, (1981)
[6] A. Tsvyashchenko, et al., *Journal of Less Common Metals* **99**, 2, L9 (1984)

Magnetic and crystal structure of MnGe studied by powder neutron diffraction.

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We have performed a powder neutron diffraction study of the magnetic and crystal structures of MnGe [1]. A polycrystalline sample of MnGe was synthesized under high pressure by a melting reaction with Mn and Ge. Below 170(5) K MnGe has a helical spin structure, with high ordered moment. The helical wavelength changes with temperature and the structure possibly locks in to a commensurate structure below 30 K. All these features reflect an original behavior respect to the other compounds of the *B*20 family.

The onset of the helical order coincides with a symmetry lowering. We consider the structural relationships between the crystal structures of known Mn-Ge compounds to search for new structural types for a given chemical composition MnGe. The onset of chiral magnetic order in the non - chiral crystal structures (tetragonal or orthorhombic) is discussed.

References

[1] O. L. Makarova, A. V. Tsvyashchenko, G. Andre, F. Porcher, L. N. Fomicheva, N. Rey, and I. Mirebeau, *Phys. Rev. B* **85**, 205205 (2012)

High-frequency spin excitations in $Cr_{1/3}NbS_2$ helimagnet

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Incommensurate magnetic structures are intrigue objects of the solid state physics. The pressing problem is the influence of the magnetic anisotropy on a magnetic phase diagram and a spectrum of the spin excitations. The aim of the present work is to establish how magnetocrystalline anisotropy influents on spin excitation in the chiral "easy-plane" helimagnet $Cr_{1/3}NbS_2$.

High frequency spin excitations were studied by ferromagnetic resonance (FMR) method. At low temperature (T < 50 K) FMR spectra consist of two lines with different temperature dependences of resonance fields H_{res} (Fig. 1). The line I with "usual" ferromagnetic temperature dependence of resonance field corresponds to homogeneous (q = 0) magnetization precession in a helical phase. The resonance field of the line I is determined by uniaxial magnetocrystalline anisotropy K_2.

The line II with "abnormal" temperature dependence of resonance field corresponds to the Goldstone mode with a wave factor q = ±Q (Q is wave vector of the modulated magnetic structure). The finite value of the Goldstone mode energy q = ±Q is due to magnetocrystalline anisotropy in basal *ab* plane. Unusual temperature dependence of the resonance field is explained by decreasing of anisotropy constant K_6 with temperature increasing. For the first time, it has been shown experimentally that effective excitation of the Goldstone mode is realized only when microwave magnetic field vector **h** is perpendicular to magnetic structure modulation vector Q.

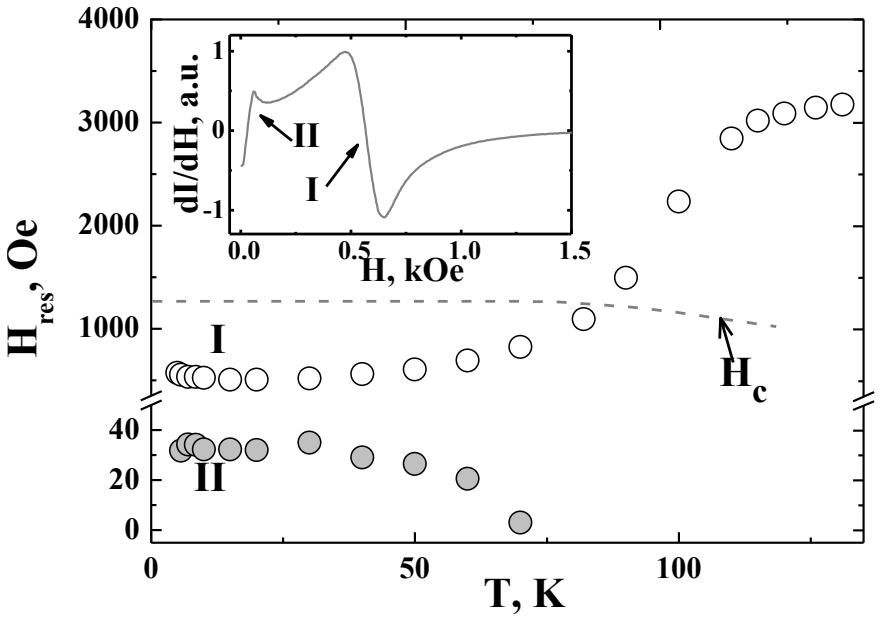

Fig. 1 *Temperature dependences of resonance fields of lines I and II for $Cr_{1/3}NbS_2$ single crystal, $H \perp c$ ($\perp Q$). Critical field of transition to ferromagnetic state is shown by dashed line. FMR spectra at T = 5 K is shown on inset.*

Session 4. Thin films of cubic ferromagnets without center of symmetry.

Chairman: Dr. Ulrich Roessler

Dzyaloshinskii-Moriya interaction in 2D magnets

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The Dzyaloshinskii-Moriya interaction (DMI) exists in any thin surface magnetic layer due to lack of the mirror symmetry [1]. DMI destroys commensurate magnetic order in ferromagnets giving rise to a helical structure [2, 3]. The same is true for antiferromagnets.

In general form helical structure is described by Kaplan expression which preserves spin commutation rules [4, 6]. The sum of the exchange energy and DMI is divided into three terms: the renormalized exchange Hamiltonian, anisotropy in the spin rotation plan ĉ and umklapp term which mixes excitations with momenta $\mathbf{q}$ and $\mathbf{q} \pm \mathbf{k}$ [5, 6]. Relative orientation of the helix wave-vector k and ĉ depends on the form of DMI.

In antiferromagnetic square lattice, the ground state is a cycloid. Spins rotate in ĉ plane which is perpendicular to the layer. The cycloid wave-vector $\mathbf{k} = \pi(1,1)+\kappa$, $\kappa \perp$ ĉ and $|\mathbf{k}|=2D/J$, where J and D are exchange interaction and DMI, respectively. In zero magnetic field ĉ || (1,1).

In-plain field rotates $\hat{c}$ to the field and ĉ || **H** at $H > H_f \sim D^2 / J$, H_f depends on the field direction. Perpendicular field destroys cycloid at $H>2SD$ and AF order is restored. Square of the spin-wave energy, q<<1 and near AF (1,1) point. Umklapp interaction mixes these modes. We have 2D spin-waves. At T>0 fluctuations must destroy long-range order. Umklapps gives rise to spin-wave gap. The gap saves the cycloid. Similar results take place in *2D* ferromagnets.

References

[1] A. Crepieux and C. Lacroix, *JNNN* **182,** 341 (1998)
[2] Y. Vedmedenko at al., *Phys. Rev.* **75,** 104431 (2007)
[3] P. Bak and M. Jensen, *J. Phys.* **C 13,** 881 (1980)
[4] T. Kaplan, *Phys. Rev.* **124,** 329 (1961)
[5] D. Belitz, T.R. Kirkpatrick and A. Rosh, *Phys. Rev. B* **73,** 054431 (2006)
[6] S.V. Maleyev, *Phys. Rev.* **73,** 174492 (2006)

Chiral Magnetic States in MnSi thin films

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Epitaxial MnSi thin films deposited onto Si(111) represent a new class of materials, where novel spin textures are stabilized over a broad range of thermodynamic parameters.[1-4] In nanostructured MnSi, a skyrmion phase is extended over a large range of fields and temperatures.[4-6] Epitaxial thin films of MnSi,[1-4] as well as the related FeGe/Si(111) [6] and (Fe,Co)Si/Si(111) [7] systems have the important advantage of making complex magnetic textures accessible to a broad range of characterization tools that enable an investigation into how skyrmions are stabilized over a much broader temperature range than in bulk crystals. We show that epitaxially induced strain and finite size effect creates two novel states in MnSi thin films: discrete helicoidal states and elliptically distorted skyrmions. Both of these states are considered as promising objects for new types of magnetic storage technologies.

The helical state unwinds in an in-plane magnetic field via discrete transitions to states with a quantized number of turns of the magnetization (Fig. 1) in contrast to the continuous evolution observed in bulk helimagnets.[8] By extension of Dzyaloshinskii's model,[9] we show that the truncation of the helicoids by the presence of the film interfaces produces a wavelength dependent Zeeman energy that stabilizes the discrete states. We investigated the unwinding with SQUID magnetometry, magnetoresistance measurements and with polarized neutron reflectometry (PNR), and find that all three sets measurements are in good agreement with the model. Furthermore, we demonstrate the concept of a novel helicoid magnetic memory where information can be stored in the number of turns in the helicoid and the discrete states can be read by electronic means.

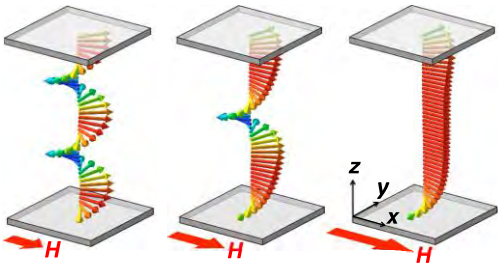

Fig. 1 *The helical unwinding of the helicoidal magnetic order in a helical magnetic thin film in an in-plane magnetic field. The film thickness is 2.14 L_D, which supports the three discrete states shown.*

Above a certain critical field, the helicoids undergo a field-induced first-order magnetic phase transition into a skyrmion state. The phase diagram is mapped with static susceptibility measurements obtained from SQUID magnetometry as a function of anisotropy, temperature and thickness. Unlike previously reported skyrmions in FeGe thin films,[6] or MnSi thinned crystals,[5] the skyrmions in MnSi films on Si(111) have their cores in the plane of the film due to an easy-plane uniaxial anisotropy created by the epitaxially induced tensile strain.[3,4] The existence of the in-

plane skyrmion phase is supported by the comparison of PNR measurements to 3-dimensional energy minimization calculations.

Our study establishes that MnSi thin films are a system where anisotropy can be engineered to stabilize novel magnetic textures. Since these films are grown on Si substrates, this opens the possibility to investigate spin-dependent transport effects in chiral magnetic heterostructures.

References

[1] E. Karhu, S. Kahwaji, T. L. Monchesky, C. Parsons, M. D. Robertson, and C. Maunders. *Phys. Rev. B* **82**, 184417 (2010)

[2] E. A. Karhu, S. Kahwaji, M. D. Robertson, H. Fritzsche, B. J. Kirby, C. F. Majkrzak, and T. L. Monchesky. *Phys. Rev B* **84**, 060404 (2011)

[3] E. A. Karhu, U. K. Rößler, A. N. Bogdanov, S. Kahwaji, B. J. Kirby, H. Fritzsche, M. D. Robertson, C. F. Majkrzak, and T. L. Monchesky. *Phys. Rev. B* **85**, 094429 (2012)

[4] M. N. Wilson, E. A. Karhu, A. S. Quigley, U. K. Rößler, A. B. Butenko, A. N. Bogdanov, M. D. Robertson, and T. L. Monchesky, *Phys. Rev. B* **86**, 144420 (2012)

[5] A. Tonomura, X. Yu, K. Yanagisawa, T. Matsuda, Y. Onose, N. Kanazawa, H. S. Park, and Y. Tokura, *Nano Lett.* **12**, 1673 (2012)

[6] S. X. Huang and C. L. Chien. *Phys. Rev. Lett.* **108**, 267201 (2012)

[7] N. A. Porter, G. L. Creeth, and C. H. Marrows, *Phys. Rev. B* **86**, 064423 (2012)

[8] Y. Togawa, T. Koyama, K. Takayanagi, S. Mori, Y. Kousaka, J. Akimitsu, S. Nishihara, K. Inoue, A. S. Ovchinnikov, and J. I. Kishine, *Phys. Rev. Lett.* **108**, 107202 (2012)

[9] I. E. Dzyaloshinskii, *Sov. Phys. JETP* 19, 960 (1964), [Zh. Eksp. Teor. Fiz. **46**, 1420 (1964)]

Topological Hall effect in epitaxially strained B20 $Fe_{1-x}Co_xSi$ films

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Crystals with the non centrosymmetric B20 structure can exist in two equivalent chiral structures. Unlike seeding growth processes, thin film deposition lacks the symmetry breaking necessary to create films with unique structural chirality and both left and right handed structures are expected. Because the B20 structure lacks inversion symmetry of the spin sites chiral magnetic textures can form. In $Fe_{1-x}Co_xSi$ these have been shown to oppose the chirality of the underlying crystal [1]. Consequently, in a system with chiral grain structure one would anticipate a ground state of neighboring helices with opposite magnetic chirality. With the application of a small magnetic field skyrmion crystals can form which are stabilised with respect to helical ground state in the presence of uniaxial distortions [2] which contributes to extended skyrmion phases in reduced dimensions and epilayers. Although only observed in recent years, these skyrmion textures appear ubiquitous amongst the magnetic B20 alloys and having (amongst others) been observed directly in $Fe_{1-x}Co_xSi$ [3] and FeGe [4].

$Fe_{1-x}Co_xSi$ epitaxial thin films grown in Leeds by MBE [5] show enhanced magnetic properties relative to bulk including larger ordering temperatures whilst still retaining the characteristically high spin polarisation. These enhancements are attributed to epitaxial strain due to the significant (~5.6 %) lattice mismatch. The films appear single crystal from XRD, LEED and TEM yet dark field TEM analysis [6] reveals the presence of crystal grains of opposite chirality ~ 100 nm across. Polarised neutron reflectometry was used to confirm the presence of periodic magnetic textures determining the helical period for $x = 0.3$ to be 9.3 nm in contrast to the 42 nm measured for bulk [1]. Such reduced spin textures have been previously observed in epilayers of MnSi [7,8] in conjunction with enhanced ordering temperatures.

Hall transport and magnetetometry were used to ascertain the topological contribution to the Hall effect arising from the Berry phase accumulated by conduction electrons traversing these real-space skyrmion textures. Below 100 K we confirm skyrmions existing over an extended temperature range (Fig. 1). We attribute the very large Hall effect (ρ_{THE} ~ 700 nΩ.cm at 5 K) to the relatively small spin textures, large Hall coefficient and high spin polarisation in $Fe_{0.7}Co_{0.3}Si$.

The authors would like to acknowledge funding from EPSRC.

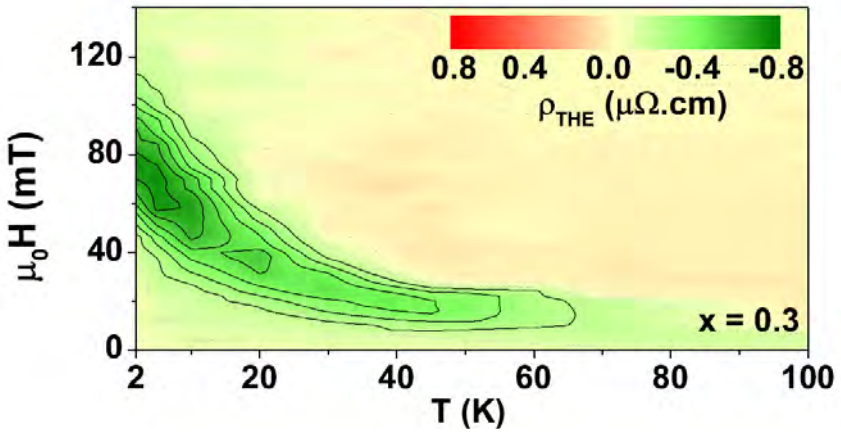

Fig. 1 *Phase diagram for skyrmion textures in an epitaxial $Fe_{0.7}Co_{0.3}Si$ (50 nm) film.*

References

[1] V. A. Dyadkin *et al.*, *Phys. Rev. B*, **84**, 014435 (2011)
[2] A. B. Butenko *et al.*, *Phys. Rev. B*, **82**, 052403 (2010)
[3] X. Z. Yu *et al.*, *Nature* **465**, 901, (2010)
[4] X. Z. Yu *et al.*, *Nat. Mater.* **10**, 106, (2011)
[5] Porter *et al.*, *Phys. Rev. B* **86**, 064423 (2012)
[6] E. A. Karhu *et al.*, *Phys. Rev. B*, **84**, 060404 (2011)
[7] E. A. Karhu *et al.*, *Phys. Rev. B*, **85**, 094429 (2012)
[8] Y. Li *et al.*, *Phys. Rev. Lett.* **110**, 117202 (2013)

Magnetic and transport properties of MnSi thin films

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The ferromagnetic compound MnSi has recently attracted great interest because of the variety of its different magnetic phases. The competition of ferromagnetic exchange with the Dzyaloshinskii-Moriya interaction causes a helical spin structure as the ground state of the system. The helix transforms into a conical structure at magnetic fields exceeding 0.1 T, and ferromagnetic alignment can be observed above 0.6 T. In addition, a skyrmion lattice phase occurs in a small field and temperature region close to the ordering temperature, which is known as the A-phase.

The reduction of the dimensionality from bulk to thin films is expected to lead to a larger skyrmionic phase in the magnetic phase diagram [1], as the stability of skyrmions is advantaged by the presence of uniaxial anisotropy, which is induced by surface effects and strain.

Using molecular beam epitaxy we have grown MnSi thin films on Si(111) substrates by simultaneous deposition of manganese and silicon. Magnetization and magnetoresistivity measurements have been carried out and related to the magnetic phase diagram. We observe an enhanced ordering temperature T_{ord} of 43 K for films thicker than 10 nm and a strong thickness dependence of T_{ord} for the thinnest films. We explain the decrease of T_{ord} observed for films thinner than 10 nm by the reduction of spin-spin interactions in the vicinity of the film surface [2].

In comparison to bulk MnSi the critical magnetic fields of the thin films are enhanced, which is interpreted as an effect of shape anisotropy that favors spin alignment in the film plane. Furthermore we can identify several features occuring in the magnetization as well as in the magnetoresistivity measurements, which are not present in bulk material. Potentially these are indications of an enlarged skyrmionic phase.

More evidence for the existence of a phase containing skyrmions is given by Hall Effect measurements, where a topological contribution is observed. This effect has recently been shown to be due to skyrmions [3].

References

[1] A. B. Butenko, A. A. Leonov, U. K. Rößler and A. N. Bogdanov, *Phys. Rev. B* ***82***, 052403 (2010)
[2] J. Engelke, T. Reimann, L. Hoffmann, S. Gass, D. Menzel and S. Süllow, *J. Phys. Soc. Jpn.* ***81***, 124709 (2012)
[3] Y. Li, N. Kanazawa, X. Z. Yu, A. Tsukazaki, M. Kawasaki, M. Ichikawa, X. F. Jin, F. Kagawa and Y. Tokura, *Phys. Rev. Lett.* ***110***, 117202 (2013)

Session 5. Antiferromagnets without center of symmetry.

Chairman: Dr. Dmitry Yu. Chernyshov

The sense of the Dzyaloshinskii–Moriya vector in canted antiferromagnets

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At the first conference of this series, DMI-2011 in St-Petersburg, we discussed an idea how to measure the *sense* of the Dzyaloshinskii–Moriya (DM) vectors in canted antiferomagnets. Now it has been experimentally determined for the FeBO3 crystal using the interference between magnetic and resonant channels in synchrotron x-ray scattering and the results are presented in this report.

The complex interplay between magnetism and atomic crystal structure, being very important, for instance, for multiferroics and spintronics, had been initially studied a long time ago for materials called canted antiferromagnets or weak ferromagnets. It was recognized that a small intrinsic canting of neighboring magnetic moments $\mathbf{s_1}$ and $\mathbf{s_2}$, observed in crystals like $MnCO_3$, $CoCO_3$, α-Fe_2O_3, $FeBO_3$, and many others, is managed by a rather weak relativistic interaction of spin-orbit origin introduced by Dzyaloshinskii and Moriya [1,2]: $E_{DM}=\mathbf{D}\bullet[\mathbf{s_1}\times\mathbf{s_2}]$, where $\mathbf{D}$ is the Dzyaloshinskii–Moriya pseudovector. Later it was recognized that the sign of the DM interaction determines the sign of magnetic helices observed in *non-centrosymmetrical* MnSi-type crystals [3].

However, even in the globally *centrosymmetrical* rhombohedral crystals of $FeBO_3$ (its structure is similar to $MnCO_3$, they have the same space group $R\bar{3}c$ the local DM vector $\mathbf{D}$ is not zero for neighboring magnetic Fe atoms because there is no inversion center between those atoms. If we consider only iron and boron atoms, the symmetry of the crystal would be $R\bar{3}m$ and the DM vector should be equal to zero. If the oxygen atoms would be positioned exactly between two neighbouring iron atoms, the symmetry would be again $R\bar{3}m$. Thus just the shift of oxygen atoms reduces the crystal symmetry from $R\bar{3}m$ to $R\bar{3}c$ making the environment of Fe-Fe bonds asymmetric and the DM vector possible. The physical reason for this shift is to reach a more close packing of the atoms in the structure.

The sense of the local $\mathbf{D}$ vector determines the sign of twist between $\mathbf{s_1}$ and $\mathbf{s_2}$. It was suggested recently [4] how to measure the sense of local $\mathbf{D}$ in centrosymmetric crystal: if we apply an external magnetic field, then the weak ferromagnetic moment is oriented along the field and the sense of local $\mathbf{D}$ fixes the phase of antiferromagnetic ordering. To measure the phase, we used a novel experimental technique based on interference between two x-ray scattering processes, magnetic scattering and resonant quadrupole-quadrupole scattering (the latter acts as a 'reference wave'). A single crystal of $FeBO_3$ is studied this way. For both scattering channels we calculate the scattering amplitudes, their interference, and from comparison with experimentally observed intensities we obtain the sense of $\mathbf{D}$ vector.

The experimental measurements are supported by *ab initio* calculations of the DM interaction in $FeBO_3$ crystal. We have performed first-principles calculations by using Local Density Approximation incorporating the on-site Coulomb interaction U and the Spin-Orbit coupling (LDA+U+SO). The latter leads to orbital magnetism and is responsible for magnetocrystalline single-site anisotropy and DM interaction between magnetic moments. Similar calculations were successfully used before for DM interaction in α-Fe_2O_3 and La_2CuO_4 crystals [5,6]. Our calculations

predict that the lowest energy stable magnetic structure is precisely the one observed experimentally. Furthermore, we predict that the magnetic twist between adjacent layers is in the same direction as the twist of the oxygen triangles between Fe layers. This coincides with experimentally determined sense of **D** vector discussed above. In addition to the sign of twist, we calculate the canting angle very close to the experimental value of 0.9°. These experimental and theoretical approaches open up new possibilities for exploring, modeling and exploiting novel magnetic and multiferroic materials.

VED and ENO are grateful to the RFBR research project No. 13-02-00760 and to the project of the Presidium of the Russian Academy of Sciences "Diffraction of synchrotron radiation in multiferroics and chiral magnetics". The work of VVM is supported by the grant program of President of Russian Federation MK-5565.2013.2, the contracts of the Ministry of education and science of Russia N 14.A18.21.0076 and 14.A18.21.0889. MIK acknowledges a financial support by FOM (The Netherlands). We thank the staff of ESRF BM-28 for expert assistance, and Yuri Shvyd'ko for the loan of the $FeBO_3$ crystal.

References

[1] I. Dzyaloshinsky, *Sov. Phys. JETP* **5**, 1259 (1957); *J. Phys. Chem. Solids* **4**, 241 (1958)
[2] T. Moriya, *Phys. Rev. Lett.* **4**, 228 (1960); *Phys. Rev.* **120**, 91 (1960)
[3] P. Bak, M. H. Jensen, *J. Phys. C: Solid State Phys.* **13**, L881 (1980)
[4] V. E. Dmitrienko, E. N. Ovchinnikova, J. Kokubun, and K. Ishida, *Pis'ma Zh. Eksp. Teor. Fiz*. **92**, 424 (2010); *JETP Lett*. **92**, 383 (2010)
[5] V. V. Mazurenko and V. I. Anisimov, *Phys. Rev. B* **71**, 184434 (2005)
[6] M. I. Katsnelson, Y. O. Kvashnin, V. V. Mazurenko and A. I. Lichtenstein, *Phys. Rev. B* **82**, 100403 (2010)

On the DMI in multiferroics RMn_2O_5

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Magneto-electric coupling in the multiferroics family RMn_2O_5 (R = rare earth) is very strong, leading to variety of spectacular effects such.

The microscopic mechanism, leading for such a strong coupling between magnetization and the electrical polarization still is questionable, though a number of theoretical models were proposed. These latter can be considered in a frames of two main mechanisms, which were proposed to explain the appearance of ferroelectricity in RMn_2O_5.

First of them is based on the antisymmetric interaction, the electrical polarization arise from a combination of atomic displacements and electronic rearrangements which would minimize the antisymmetric interaction between non-collinear spins. Such mechanism is usually referred as *inverse Dzyaloshinsky-Moria effect*, the polarization can be expressed as $\mathbf{P} \sim \mathbf{e}_{12}\times[\mathbf{S}_1\times\mathbf{S}_2]$, where $\mathbf{S}_1$, $\mathbf{S}_2$ – spins on the adjacent sites along the c-axis and $\mathbf{e}_{12}$ – unit vector, connecting them [1]. This mechanism seems to explain well the origin of ferroelectricity in many systems investigated, for example, in $TbMnO_3$ [2].

Another mechanism - exchange striction: electrical polarization arises due to atomic displacements, which take place in order to remove the exchange degeneracy. This model does not require the non-collinearity and intrinsically stronger then DM. In spite of great amount of experimental work on RMn_2O_5, it is very difficult to make the choice between these two models.

Our recent neutron investigations of the single crystals of $Tb_{1-x}Ce_xMn_2O_5$ (x =0, 0.20, 0.25), $NdMn_2O_5$, $EuMn_2O_5$ give the reason to make the essential accent on the Dzyaloshinsky-Moria interaction in RMn_2O_5. Thus, electron doping (by Ce) of the $TbMn_2O_5$ produces the changes in the Mn^{4+} subsystem – along c-axis. This modification changes the k_z-component of magnetic propagation vector and at the same time stabilizes the k_x-component to be equal to 0.5 [3]. The similar situation takes place in $NdMn_2O_5$. The bigger size of Nd^{3+} ion produces the considerable change in the ratio between exchange paths along *c*-axis. As it is expected, it has an effect on k_z-component of magnetic propagation vector but also stabilizes k_x-component (to be equal to 0) [4]. This effect can be understood, if we consider of the model of DMI, where effective antisymmetric interaction along *z*-axis is mediated by the Mn^{3+} ions. This model gives the expression for the DM energy, which connects the spin components in *z*-direction (*c*-axis) and in *ab*-plane [5]:

$$E_{DM} = -D\acute{s}_x s_z \sin(\alpha/2),$$

where $\acute{s}_x$ – Mn^{3+} spin component in *ab*-plane, s_z – Mn^{4+}spin component along *z*-axis (*c*-axis), $\alpha/2$ – phase of the spins.

Our polarized neutrons experiments on $TbMn_2O_5$ and $EuMn_2O_5$ give strong evidence that in these systems s_z component does present [6]. And, it is impossible to explain the existence of s_z component in RMn_2O_5 without involvement DMI, since the exchange striction model as well as the competition between nearest-neighbor and next-nearest-neighbor interactions cannot explain that fact.

Thus, our results give the evidence that DMI in RMn_2O_5 is realized as leading mechanism in the magnetic ordering formation, and could be taken in consideration as driving force in the magneto-electric coupling in these compounds.

The work is fulfilled with the support of RFBR grant 11-02-01363-a, and MES grant 16.518.11.7034.

References

[1] M.Mostovoy, *Nat. Mater.* ***7***, 269 (2008)
[2] S-W.Cheong, M.Mostovoy, *Nat. Mater.* ***6***, 13 (2007)
[3] I.A.Zobkalo, S.V.Gavrilov, V.A.Sanina, E.I.Golovenchits, *Fizika Tv. Tela* (in russian, in press)
[4] I.A. Zobkalo, S.V. Gavrilov, A.A. Kuncevich, S.N. Barilo, S.V. Shiryaev, *Preprint PNPI* ***2915*** (2012)
[5] P.G.Radaelli, L.C.Chapon, *J.Phys.: Conens. Matter* ***20***, 434213 (2008)
[6] I.A. Zobkalo, V.A. Polyakov, S.V. Gavrilov, E.K. Dimakova, *Flipper 2013 (abstracts)*, 146 (2013)

Local spin canting in cubic helimagnetics MnSi and Cu_2OSeO_3

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In classical Heisenberg theory of twisted magnetics the energy density of a spin structure can be written as [1,2]

$$E = \frac{1}{2}\sum_i \sum_j \left(-J_{ij}\vec{s}_i \cdot \vec{s}_j + \vec{D}_{ij} \cdot \left[\vec{s}_i \times \vec{s}_j\right]\right),$$

where *i* enumerates all the magnetic atoms in the unit cell, *j* does the neighbors of the *i*th atom, $\vec{s}_i$ is classical spin ($|\vec{s}_i| = 1$), J_{ij} are the exchange constants (J>0 for ferromagnetics), $\vec{D}_{ij}$ are the Dzyaloshinskii-Moriya (DM) vectors. Earlier [3,4] it was shown for the MnSi-type magnetics with *B*20 structure how the transition from the Heisenberg model to the phenomenological free energy can be performed, if we take into account the spin canting between several magnetic sublattices of the crystal.

Here, we assert that, in twisted magnetics, two different kinds of canting should be distinguished: the first one determined by the DM interaction, and the second one connected with the magnetization gradients. The latter inevitably occurs in the twisted magnetic states, if the unit cell of the crystal contains n>1 magnetic atoms, because in that case n spin helices appear with the same propagation vector but with small phase shifts relative to the macroscopic helix. In order to discount these phase shifts, it is convenient to introduce for magnetic atoms the so called "exchange positions" (Fig. 1) depending on the exchange parameters J_{ij}. In the case of the cubic helimagnetics with almost collinear spins, e.g. MnSi and Cu_2OSeO_3, the appropriate condition for the exchange positions is $\sum_j J_{ij} c_j \vec{b}_{ij} = 0$, where $c_j = \pm 1$ designates direction of the *j*th spin relative to the average magnetization direction $\vec{\mu}$, and $\vec{b}_{ij}$ is the vector connecting imaginary positions of the *i*th and *j*th atoms. Then, the elastic energy density of the magnetic structure can be written in the conventional form [5-7] as

$$E = \tilde{J}\frac{\partial \mu_i}{\partial x_k}\frac{\partial \mu_i}{\partial x_k} + \tilde{D}\vec{\mu} \cdot \left[\vec{\nabla} \times \vec{\mu}\right],$$

where "phenomenological" constants $\tilde{J}$ and $\tilde{D}$ are now expressed through the microscopic parameters J_{ij} and $\vec{D}_{ij}$:

$$\tilde{J} = \frac{1}{12}\sum_i \sum_j J_{ij} c_i c_j b_{ij}^2,$$

$$\tilde{D} = -\frac{1}{6}\sum_i \sum_j c_i c_j \vec{D}_{ij} \cdot \vec{b}_{ij}.$$

In these simple additive expressions, each bond between magnetic atoms makes contributions of similar form. The expressions reveal nonlinear behavior, because the bonds $\vec{b}_{ij}$ depend on the exchange coordinates.

Using the above equations with $c_i, c_j = +1$, the parameters $\tilde{J}$ and $\tilde{D}$ for the MnSi-type helimagnetics can be easily obtained considering non-nearest neighbors [8]. It is found that just the interplay between the exchange parameters of several magnetic shells rather than the signs of DM vectors could be responsible for the concentration-induced reverse of the magnetic chirality observed

recently in $Mn_{1-x}Fe_xGe$ [9]. In the case of ferrimagnetic Cu_2OSeO_3 ($c = -1/+1$ for the Cu-I/Cu-II atoms), the phenomenological constants can be found numerically, using J_{ij} and $\vec{D}_{ij}$ values known from *ab initio* calculations (see, e.g., DFT+U+SOC calculations in [10]). Using the data from [10], we find $\tilde{J}$ = 2.565 meV, $\tilde{D}$ = -0.379 meV, and propagation number $k = \tilde{D}/2\tilde{J}$ = -0.0738 (the sign "minus" means left-handed magnetic structure). This value of k lies between the estimation made without taking the canting into account ($|k|$=0.0653) and the experimentally observed one ($|k|$=0.0880) [10].

The relative canting of magnetic moments due to the DM interaction inside a unit cell is also considered. It is found that the spin tilts of this kind still remain, when the magnetic structure is unwound by the strong enough magnetic field. In [4] we proposed neutron and x-ray diffraction experiments to find the canting in the MnSi-type helimagnetics. Similar technics can be used for Cu_2OSeO_3, where the spin tilts are more noticeable for the Cu-II atoms (about 4°), Fig. 2.

This work was supported by two projects of the Presidium of the Russian Academy of Sciences: "Matter at high energy densities; Substance under high static compression" and "Diffraction of synchrotron radiation in multiferroics and chiral magnetics".

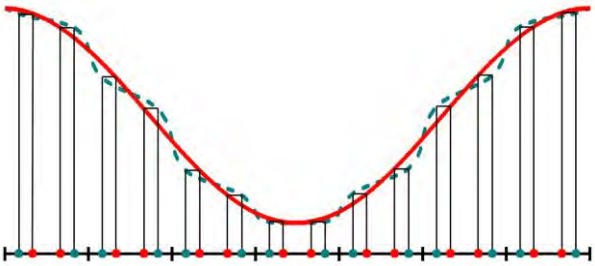

Fig. 1 *Why it is convenient to introduce imaginary „exchange positions". The initial curve (dash cyan) is plotted with the use of the function values given in the discrete set of points with the coordinates x and -x within the cells of a 1D crystal. When the points are shifted to the center of the cells without a change of function values, the view of the curve changes to more smooth (solid red).*

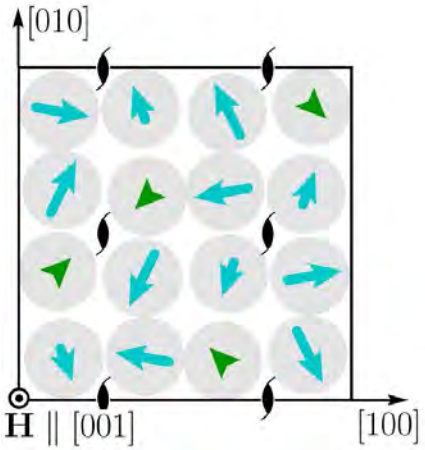

Fig. 2 *The spin cantings in the ferrimagnetic state of Cu_2OSeO_3, induced by the external magnetic field applied in the [001] direction. Darts and arrows correspond to 4 Cu-I and 12 Cu-II atoms.*

References

[1] T. Moriya, *Phys. Rev. Lett.* **4**, 228 (1960)
[2] T. Moriya, *Phys. Rev.* **120**, 91 (1960)
[3] V. A. Chizhikov, V. E. Dmitrienko, *Phys. Rev. B* **85**, 014421 (2012)
[4] V. E. Dmitrienko, V. A. Chizhikov, *Phys. Rev. Lett.* **108**, 187203 (2012)
[5] I. E. Dzyaloshinsky, *Sov. Phys. JETP* **5**, 1259 (1957)
[6] I. Dzyaloshinsky, *J. Phys. Chem. Solids* **4**, 241 (1958)
[7] P. Bak, M. H. Jensen, *J. Phys. C: Solid State Phys.* **13**, L881 (1980)
[8] V. A. Chizhikov, V. E. Dmitrienko, http://arxiv.org/abs/1211.1517 (submitted to PRB)
[9] S. V. Grigoriev, N. M. Potapova, S.-A. Siegfried, V. A. Dyadkin, E. V. Moskvin, V. Dmitriev, D. Menzel, C. D. Dewhurst, D. Chernyshov, R. A. Sadykov, L. N. Fomicheva, and A. V. Tsvyashchenko, to be published in *Phys. Rev. Lett.*
[10] J. H. Yang, Z. L. Li, X. Z. Lu, M.-H. Whangbo, Su-Huai Wei, X. G. Gong, and H. J. Xiang, *Phys. Rev. Lett.* **109**, 107203 (2012)

Helical antiferromagnetic structure induced by charge density wave, in the high pressure cubic phase $TbGe_{2.85}$

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We have investigated the magnetic structure in a polycrystalline sample of the new high pressure synthesized compound $TbGe_{2.85}$ by means of neutron diffraction and ^{111}Cd – TDPAC methods. It has the cubic $AuCu_3$ crystal lattice ($Pm\bar{3}m$ space symmetry) with a = 4.287 Å [1]. Magnetic measurements showed that $TbGe_{2.85}$ exhibits the antiferromagnetic-type ordering below T_N = 19 K. The magnetic susceptibility of $TbGe_{2.85}$ follows a Curie-Weiss law above 50 K with an effective magnetic moment μ_{eff} = 9.65 μ_B/f.u. and θ_p = - 46 K. Below 19 K $TbGe_{2.85}$ has a helical antiferromagnetic spin structure with the wavevector k = $2\pi/a$(ξ_x, 0, ξ_z), where ξ_x = 0.5 and ξ_z = 0.1616, which is incommensurate with the period of the spiral λ = 23,7 Å (see Fig.1). The magnetic moment value 7.8 μ_B for Tb was found. It is lower than the Tb^{3+} free-ion value $gJ\mu_B$ = 9 μ_B, most likely because of crystalline field effects. The $^{111}In/^{111}Cd$ nuclear probes were introduced into the lattice of $TbGe_{2.85}$. They are located at Ge sites. For ctystallographically equivalent site of Ge the electric field gradients $\boldsymbol{V_{zz}}$ (the quadrupole frequency $\boldsymbol{\nu}_Q = eQV_{ZZ}/h$) and induced hyperfine magnetic fields $\boldsymbol{B_{hf}}$ ($\boldsymbol{\omega}_M = g\mu_N B_{hf}/\hbar$ is the Larmor frequency) were measured. For T >T_N one quadrupole frequency was observed $\boldsymbol{\nu}_Q$ = 37.5(5) MHz with the asymmetry parameter $\eta = Vxx - Vyy/Vzz = 0$. In the magnetically ordered state for T < T_N the site of Ge is magnetically non-equivalent. Therefore two hyperfine magnetic fields $\boldsymbol{B_{hf1}}$ = 2.8 T and $\boldsymbol{B_{hf2}}$ = 4.0 T, induced by the magnetic moments of Tb ions (see Fig.2) arise on ^{111}Cd nuclei. The direction of hyperfine magnetic fields $\boldsymbol{B_{hf1}}$ and $\boldsymbol{B_{hf2}}$ is discussed. Also it was found that the site of Ge is electronically non-equivalent and two quadrupole modulations with nearly equal values of frequency $\boldsymbol{\nu}_{Q1}$ = 8 and $\boldsymbol{\nu}_{Q2}$ = 9 MHz arise on ^{111}Cd nuclei. This indicates that an electronic anisotropy appears at low temperature in $TbGe_{2.85}$.

The question arises why the compound $TbGe_{2.85}$ with a cubic crystal structure and the inversion center has a helical magnetic structure. The clue to answer this question may be the presence of one more transition, presumably of CDW-type found in the measurements of the electrical resistance and specific heat at T_{CDW} = 160 K (see Fig. 3). At T < T_{CDW} the charge density wave causes a loss of the inversion center (or lack of centrosymmertry) in the cubic crystal structure of $TbGe_{2.85}$ and the appearance of Dzyaloshinskii-Moriya anisotropy. The helical spin order is due to the competition between the ferromagnetic exchange interaction and DM anisotropy [2,3]. Probably the CDW propagates in the direction of [001] as well as the helical modulation. External pressure reduces T_{CDW}, but T_N is nearly pressure independent.

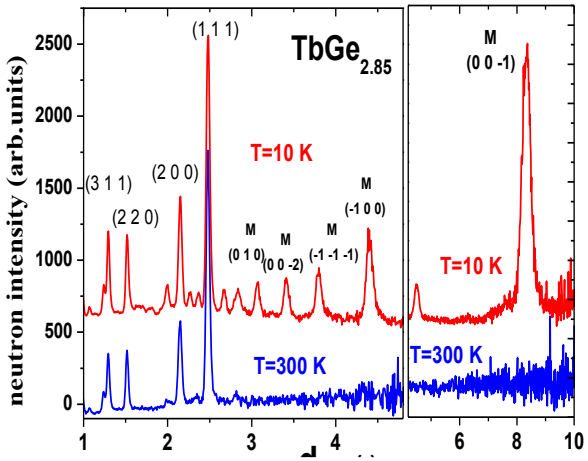

Fig. 1 *Neutron diffraction patterns of $TbGe_{2.85}$ measured on DN-12 of IBR-2 at different temperatures.*

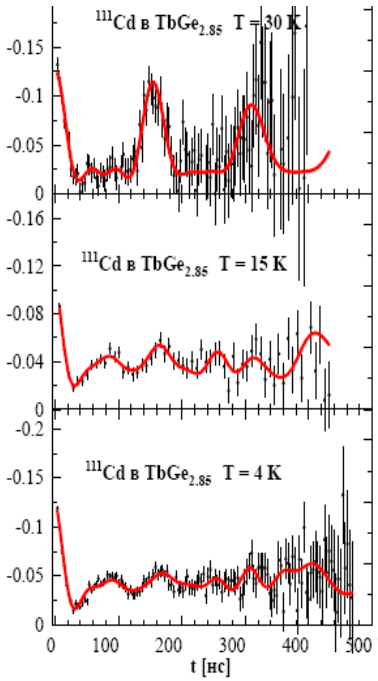

Fig. 2 *^{111}Cd- TDPAC spectra R(t) of $TbGe_{2.85}$ measured at different temperatures.*

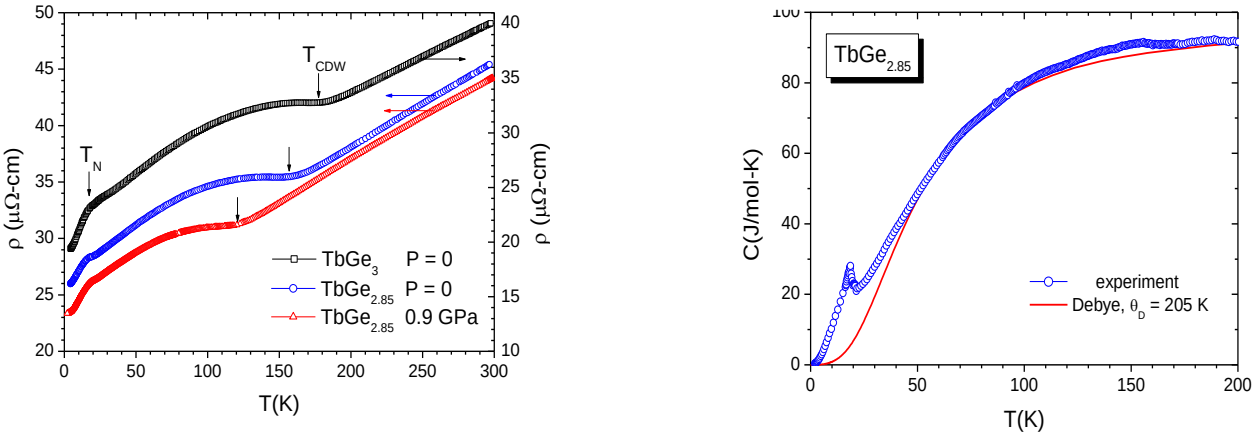

Fig. 3 *Temperature dependences of the electrical resistivity and specific heat of cubic high pressure phase $TbGe_{2.85}$*

This work was supported by the Russian Foundation for Basic Research (Grant No. 11-02-00029), the Programs of the Presidium of RAS "Physics of Strongly Compressed Matter", "Neutron Research" and ''Strongly Correlated Electrons''.

References

[1] A.V. Tsvyashchenko, et al., *J of Alloys and Compounds* **552**, 190 (2013)
[2] P. Bak and M. H. Jensen, *J. Phys. C* **13**, L881 (1980)
[3] S. V. Maleyev, *Phys. Rev. B* **73**, 174402 (2006)

Session 6. Exotic spin structures (skyrmions) in the feromagnets with DM interaction.

Chairman: Dr. Alexander S. Ovchinnikov

Multiple-*q* states in classical triangular-lattice Heisenberg antiferromagnet with frustrated interactions

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Recently, chiral helimagnets with the cubic B20-structure (like MnSi, FeCoSi and FeGe [1]) have attracted much interest because of the formation of skyrmion states – smooth, compact, two-dimensional, topological solitons. Dzyaloshinskii-Moriya interaction plays the crucial role in their stability and helps to overcome the limitations imposed by Derrick's theorem on dimensionality of finite-energy solitons [2].

Frustrated magnets provide another example of condensed-matter systems, in which non-collinear spin textures can be stabilized by competing exchange interactions. A variety of multi-*q* states have been found in numerical simulations on triangular-lattice Heisenberg antiferromagnets with competing interactions [3]. These states include skyrmion crystals stabilized by thermal fluctuations in a small pocket at the boundary with the paramagnetic state, resembling the A-phase in non-centrosymmetric helimagnets [1].

In this contribution we show that the uniaxial anisotropy can stabilize skyrmions on a triangular lattice even at zero temperature. These skyrmions have internal degrees of freedom, such as chirality and the spin-rotation angle ψ, which the skyrmions in non-centrosymmetric magnets do not have and exhibit unusual interactions with other skyrmions (attraction instead of repulsion at medium-range distances), which may have important implications for kinetics of skyrmion states in an applied magnetic field.

We focus here on the two-dimensional triangular lattice of spins with competing ferromagnetic nearest-neighbor ($J_1 > 0$) and antiferromagnetic next-nearest-neighbor ($J_2 < 0$) interactions (see inset in Fig. 1 (a)):

$$H = -J_1 \sum_{<i,j>} \boldsymbol{S}_i \cdot \boldsymbol{S}_j - J_2 \sum_{<<i,k>>} \boldsymbol{S}_i \cdot \boldsymbol{S}_j - K_{\mathrm{u}} \sum_i S_{z,i}^2 - \boldsymbol{H} \cdot \boldsymbol{S}, \qquad (1)$$

where $\boldsymbol{S}_i = (S_{x,i}, S_{y,i}, S_{z,i})$ are classical Heisenberg spins ($|\boldsymbol{S}_i| = 1$) and K_{u} is the strength of the uniaxial anisotropy. The energy (1) has been minimized using the iterative simulated annealing procedure and a single-step Monte-Carlo dynamics with the Metropolis algorithm (for details see Ref. [4]). By comparing the energies of all ordered states, we have constructed the phase diagram in the K_{u}-H plane for $J_2 / J_1 = 0.5$ (see Fig. 1 (a)). Figure 1 (b) shows the real-space spin configurations of all the found phases:

(I) *The single-q conical spiral,* which combines properties of the homogeneous ferromagnetic state and the flat spiral, is a compromise between Zeeman and exchange energies: the spin component, S_z, along the applied field has a fixed value while the spin vector $\boldsymbol{S}$ rotates within a cone surface (Fig. 1 (b)). The single-*q* spiral formed by S_x and S_y components has an in-plane propagation vector (normal to the applied magnetic field $\boldsymbol{H} \parallel z$), which breaks the threefold lattice symmetry C_3. The single-*q* state is a global energy minimum for zero and negative values of the uniaxial anisotropy.

(II) *The single-q helical spiral,* in which spins rotate in the plane normal to the *xy* plane. The applied magnetic field and the easy-axis anisotropy give rise to deviations from the circular spiral state. This modulated state is absent in the model considered in Ref. [3] and is stable in a wide range of the anisotropy constant K_u and for relatively low magnetic fields.

(III) *The double-q state*, which can be considered as a superposition of two conical spirals with the propagation vectors $\boldsymbol{q}_1$, $\boldsymbol{q}_2$ (Fig. 1 (b)). Due to the phase mismatch between two spirals, S_z is modulated along $\boldsymbol{q}_1 - \boldsymbol{q}_2$. To the left of the dotted line on the phase diagram, the amplitude of one of the superimposed spirals starts decreasing and the double-*q* phase is continuously transformed into the conical spiral.

(IV) *The triple-q state (skyrmion crystal)*, which is the superposition of three helical spirals with the propagation directions $\pm\boldsymbol{q}_1$, $\pm\boldsymbol{q}_2$, $\pm\boldsymbol{q}_3$ (preserving the three-fold symmetry of the lattice). The triple-*q* states are stabilized by the simultaneously present magnetic field and the easy-axis uniaxial anisotropy. In contrast to the chiral skyrmions in non-centrosymmetric helimagnets, the triple-*q* states have two additional degrees of freedom: the chirality (there is no energy difference between right and left-handed skyrmions) and the azimuthal angle ψ of a spin rotation with respect to the crystallographic axes. In addition, isolated skyrmions in frustrated magnets attract each other forming metastable skyrmion clusters (white shading in the phase diagram stands for the region of skyrmion clusters) with the hexagonal or square arrangements of skyrmions.

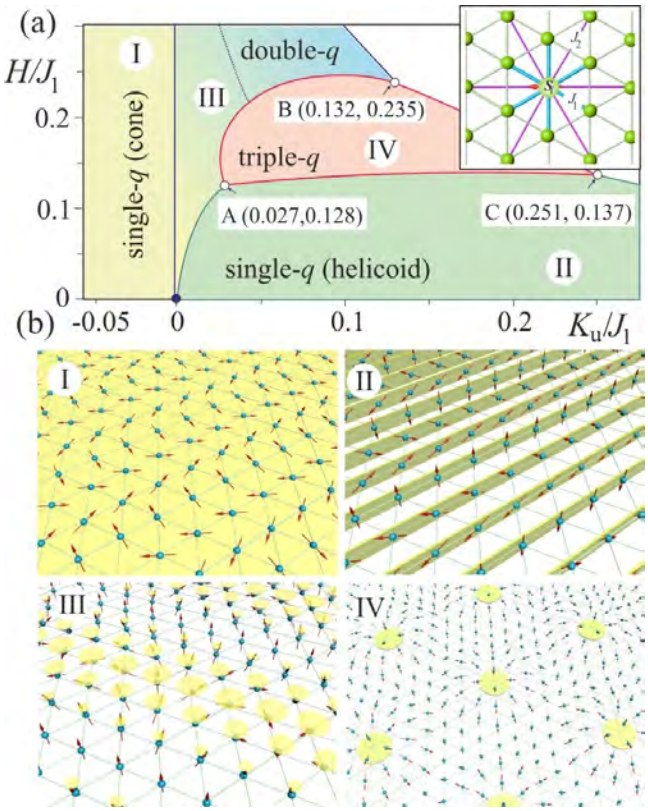

Fig.1 *(a) Phase diagram of the solutions for model (1). Filled areas designate the regions of thermodynamical stability of corresponding modulated phases; (b) structures of the modulated states.*

The authors are thankful to N. Nagaosa, Y. Tokura, S. Blügel, and U. K. Röβler for useful discussions. This study was supported by the Stichting voor Fundamenteel Onderzoek der Materie (FOM).

References

[1] H. Wilhelm, M. Baenitz, M. Schmidt, U.K. Röβler, A.A. Leonov, A.N. Bogdanov, *Phys. Rev. Lett.* **107**, 127203 (2011)

[2] R. H. Hobart, Proc. Phys. Soc. Lond. **82**, 201 (1963); G. H. Derrick, *J. Math. Phys.* **5**, 1252 (1964)

[3] T. Okubo, S. Chung, H, Kawamura, *Phys. Rev. Lett.* **108**, 017206 (2012)

[4] A. Leonov, Ph.D thesis, Dresden University of Technology, Dresden (2012)

Why do skyrmions exist in nanolayers of cubic helimagnets? Theory of confined chiral modulations

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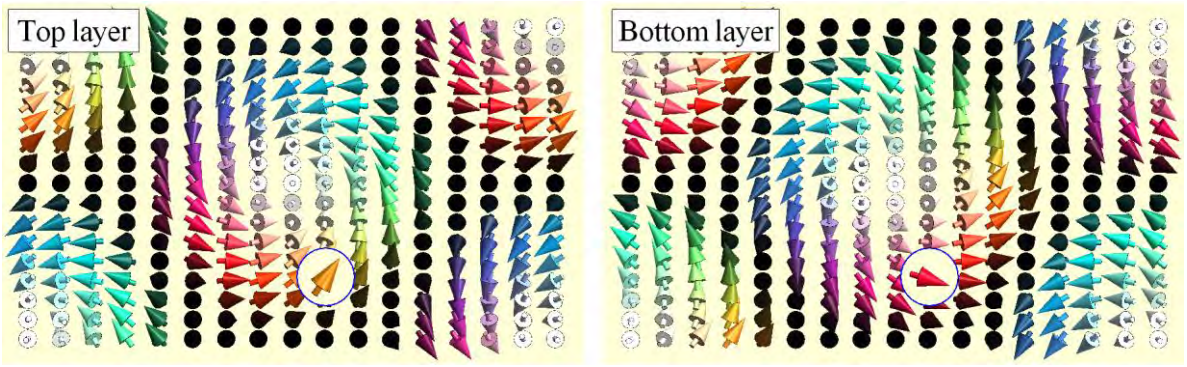
Chiral skyrmions have been predicted to exist in noncentrosymmetric ferromagnets more than two decades ago [1]. Nevertheless, when chiral skyrmions had been finally discovered in mechanically thinned films of cubic helimagnets [2], it was a kind of puzzle. The matter is that in *bulk* cubic helimagnets one-dimensional modulations (*cone* phases) corresponds to the global minimum in nearly the entire magnetically ordered region while skyrmions and helicodis can exist only as metastable states (see e.g. [3]). Thus, it was totally unclear why skyrmions, generally unstable in bulk samples, are observed in a broad range of temperatures and applied fields in thin layers of the same materials.



Here we present the results of 3D numerical calculations of chiral modulations in thin layers of cubic helimagnets [4] which resolve this puzzle and elucidate recent experiments in mechanically thinned [3] and epitaxial films [5,6] of MnSi and kindled compounds. It was found that in thin films of cubic helimagnets chiral skyrmions are modulated along three spatial directions. The structure of such 3D skyrmions roughly can be thought of as a superposition of conical modulations along the skyrmion axis and double-twist rotation in the perpendicular plane (Figure, for details see [4]). We show that chiral modulations across the layer thickness radically change the skyrmion energetics and provide a thermodynamical stability of a skyrmion lattice in a broad range of applied magnetic fields. These results disclose a basic physical mechanism underlying the formation of skyrmion states recently observed in nanolayers of cubic helimagnets. We discuss peculiarities of chiral modulations observed in [2,5,6] and a role of a surface/interface induced uniaxial anisotropy as an alternative mechanism to stabilize chiral skyrmions in confined helimagnets [5,7].

References

[1] A. N. Bogdanov, D. A. Yablonsky, *Sov. Phys. JETP* **68**, 101 (1989)
[2] X. Z. Yu, *Nature* **465**, 901 (2010); X. Z. Yu et al., *Nat. Mater*. **10**, 106 (2011); X. Z. Yu et al., *Nat. Commun*. **3**, 988 (2012); A. Tonomura et al., *Nano Lett.* **12**, 1673 (2012)
[3] H. Wilhelm et al. *J. Phys.: Cond. Matter* **24** 294204 (2012)
[4] F. N. Rybakov et al. ArXiv: 1212.5970; www.youtube.com/user/helimagnets
[5] E. A. Karhu et al., *Phys. Rev. B* **85**, 094429 (2012); M. N. Wilson et al., *Phys. Rev. B* **86**, 144420 (2012)
[6] S. X. Huang and C. L. Chien, *PRL*. **108**, 267201 (2012)
[7] A. B. Butenko et al., *Phys. Rev. B* **83**, 052403 (2010)

Spin helix in magngtic field
A-phase problem in MnSi

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Any spin helix is determined by two vectors: helix wave-vector k and normal N to the spin rotation plane. In classical approximation the helix feels magnetic field along N only and the spins are inclined on the angle $\sin\alpha = -H_{\parallel}/H_C$ where H_C is the field of the ferromagnetic transition. The perpendicular field freezes spin harmonics $S_{\pm k}$ and leads to a mixing spin-waves with momenta 0 and $\pm\mathbf{k}$. As a result we get the magnon Bose-Einstein condensation with momenta $\pm n\mathbf{k}$ where n=0,1,...

In the case of **MnS**i there is a competition between classical and BEC energies. The first order transition with k rotation perpendicular the field occurs at $H = 0.46H_C$. This result holds in the linear spin-wave theory. With further field increasing it fails and the upper boundary H_{C2} for k rotation to the field **cannot** be determined in the linear theory. In the field range between H_{C1} and H_{C2} there is a coexistence of the convention al conical pha**se** and magnetized clusters with k randomly oriented perpendicular to H**. T**hey interact as magnetic dipoles. At low T we have a dipolar glass. With **temperature** increasing the dipoles try to diminish the magnetic energy. Transition holds to hexagonal state with minimal energy.

Microscopic modeling of the S=1/2 Heisenberg ferrimagnet Cu_2OSeO_3

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Cu_2OSeO_3 is a $S = 1/2$ Heisenberg ferrimagnet with a sizable magnetoelectric coupling [1]. Recent experimental studies reported magnetic-field-induced emergence of skyrmions in this insulating material [2]. Based on extensive density functional theory (DFT) band structure calculations, we evaluate isotropic (Heisenberg) as well as anisotropic (Dzyaloshinskii-Moriya) magnetic exchange couplings.

Five relevant magnetic couplings form a complex, non-frustrated spin model, which can be described as a pyrochlore lattice of magnetic tetrahedra. A peculiar feature of this lattice is the alternation of "strong" tetrahedra (the constituent spins are strongly coupled) and "weak" tetrahedra.

Profiting from the separation of the energy scales, we develop an effective model, treating strong tetrahedra either as a classical $S = 1$ object or as a coherent quantum superposition of classical states. For the latter case, we find an excellent agreement with the quantum Monte Carlo simulations of the full model and the experimental magnetization as well as neutron diffraction data.

We demonstrate that the developed effective model can be further used to model the field-induced behavior, including the formation of skyrmions.

References

[1] J.-W. G. Bos, C. V. Colin, and T. T. M. Palstra, *Phys. Rev. B* **78**, 094416 (2008)
[2] S. Seki, X. Z. Yu, S. Ishiwata, and Y. Tokura, *Science* **336**, 198 (2012)

Ab initio evaluation of Dzyaloshinsky-Moriya interactions in magnetic insulators

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Dzyaloshinsky-Moriya (DM) interactions are an important ingredient of the complex magnetic behavior observed in magnetic insulators, such as transition-metal oxides. Ternary and quaternary oxides are natural hosts for the DM couplings because of the complex crystal structures that often have low crystallographic symmetry and polar atomic arrangement. Unfortunately, even a qualitative assessment of these couplings is generally impossible, which makes the DM interactions one of the most enigmatic aspects of real materials.

Here, we present a general computational approach to the evaluation of the DM couplings in magnetic insulators. This approach is based on density functional theory (DFT) band-structure calculations that are renowned for their highly efficient treatment of complex materials, including strongly correlated electronic systems and Mott or charge-transfer magnetic insulators. DFT-based approaches combined with the mean-field DFT+U correction for strong on-site (Hubbard) correlations are frequently used in different fields of condensed matter physics. For example, they are routinely applied to the modeling of magnetic insulators on the level of isotropic (Heisenberg) models. We show that this approach can be generalized to anisotropic interactions, including the DM terms, by performing fully relativistic DFT calculations for a set of non-collinear spin configurations with constrained magnetic moments. Our method is carefully tested on a family of Cu^{+2}-based spin-1/2 magnetic oxides that show quantum magnetic behavior at low temperatures. We obtain a good and quantitative agreement with available experimental references for spin-chain magnets ($CuSe_2O_5$, $KCuGaF_6$), spin-dimer magnets [$SrCu_2(BO_3)_2$], and the kagome-lattice mineral herbertsmithite $Cu_3Zn(OH)_6Cl_2$. Our approach further allows the prediction of DM interactions in a wide range of systems, such as the polar magnetic oxide Cu_2OSeO_3 exhibiting skyrmion physics.

Besides the evaluation of DM couplings in individual compounds, we go a step beyond and endeavor to elucidate the relationship between the spatial arrangement of the magnetic Cu^{+2} ions and the resulting DM interactions. Such trends can be useful for a better understanding of microscopic mechanisms behind the DM couplings, and for the prediction of new materials with interesting physics driven by the DM interactions.

AT and OJ acknowledge the financial support by the EU through the Mobilitas program of the ESF (Grants No. MTT77 and MJD447).

Hexagonal spin structure of A-phase in MnSi: densely packed skyrmion quasiparticles or 2D-modulated spin superlattice?

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We have studied in detail the A-phase region in the field-temperature (H-T) phase diagram of the cubic helimagnet MnSi using small angle neutron diffraction for the magnetic field applied along the principal axes of the cubic structure. In all cases the A-phase revealed itself in the neutron scattering as a two-dimensional hexagonal pattern of Bragg spots with $\mathbf{k}_{h(1,2,3)} \perp \mathbf{H}$. The directions and value of wave-vectors $\mathbf{k}_{h(1,2,3)}$ are well preserved over the whole crystal of the size of 100 mm^3, but in the small room of the (H-T) phase diagram just below T_C = 29 K.

There are two main explanations about the driving force for the A-phase structure formation: interaction between three different *q*-modes resulting in the hexagonal spin lattice [1] and nucleation/condensation of localized entities –skyrmions [2,3]. The point of controversy in these concepts can now be formulated as: does the structure of the A-phase has really a skyrmionic character, where skyrmions as quasi-particles can build clusters of the hexagonal structure with the periodicity not related to the spiral pitch? Or, may be, the A-phase is just one more consequence of the DM interaction, when two dimensionally (2D) modulated spin superlattice appears?

It is found in accord with the earlier experiments that the wavevector of 2D modulations k_h is equal to the wavevector of the cone phase k_c with accuracy of 2% for all three field-to-crystal orientations. Accounting for the three-fold symmetry of the hexagon patterns the distance between the neighboring knots in the real-space superlattice should be equal to $(2/\sqrt{3})d_s$, where d_s is the periodicity of the 1D-modulated spiral structure.

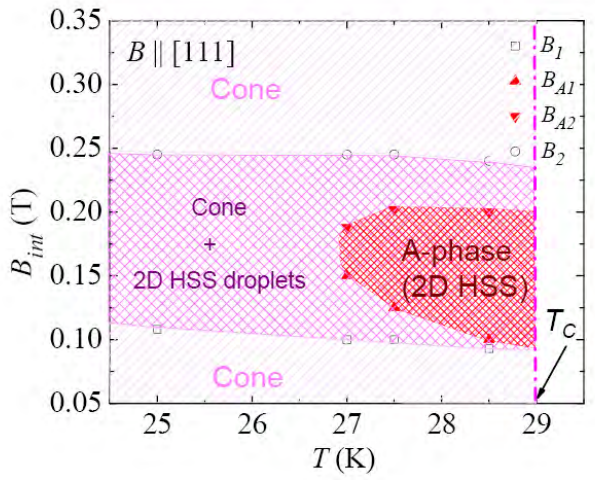

Fig.1 *(H-T) phase diagram close to the A-phase in MnSi for the field* ***H*** *applied along the [111] axis.*

The A-phase structure is replaced by the cone structure at low temperatures (Fig.1). However, the droplets of the orientationally disordered, presumably hexagonal, spin structure with $\mathbf{k}_h \perp \mathbf{H}$ are observed in the field range from $B_1 \approx 0.1$ T to $B_2 \approx 0.25$ T at temperatures down to 15 K. Nevertheless no melting of these droplets into individual randomly located skyrmions is observed for all temperatures and magnetic fields. We ascribe location of the observed droplets to the surfaces of the bulk sample under study in accordance to the results reported on the thin films using Lorentz TEM [4]. Similar to our study the two-dimensional lattice in thin films is very stable over the large temperature range.

In general, we conclude that the 2D-modulated hexagonal spin superlattice (2D HSS, or, A-phase structure) is clearly determined by the same set of the interactions (DM and ferromagnetic exchange) as the simple spiral, which is energetically favorable at zero field. This 2D-

modulated HSS rather mimics the skyrmion lattice being in reality one more curious example of the complex magnetic structures. The complexity of the structure is emphasized by the two dimensional nature of its modulations what differs it from the one-dimensional modulations of a simple spiral or conical state.

References

[1] S. Muhlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Boni, *Science* **323**, 915 (2009)
[2] U. K. Rossler, A. N. Bogdanov, and C. Pfleiderer, *Nature* **442**, 797 (2006)
[3] U.R. Rossler, A.A. Leonov, A.N. Bogdanov, *Journal of Physics: Conference Series* **303** (2011) 012105
[4] A. Tonomura, X. Yu, K. Yanagisawa, T. Matsuda, Y. Onose, N. Kanazawa, H. S. Park, and Y. Tokura, *Nano Lett.* **12** (2012) 1673-1677

Competition of the cone and A-phase in MnSi close to T_C

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The temperature evolution of the spin structures of MnSi in the magnetic field close to T_C is studied by small angle neutron scattering. Three magnetic states are observed: (i) the critical spin helix fluctuations with randomly oriented $\mathbf{k_f}$ (ii) the conical structure with $\mathbf{k}_c \parallel \mathbf{H}$ and (iii) the hexagonal A-phase structure with $\mathbf{k}_h \perp \mathbf{H}$. It is known that in zero field MnSi undergoes a complex transition from the para- to heli-magnetic phase through continuous, yet well distinguishable crossovers: (i) from paramagnetic to partially chiral state at $T_{DM} \approx 31.5$ K, (ii) then to highly chiral fluctuating state at $T_k \approx 30$ K and (iii) then to helical structure at $T_C = 29.0$ K.

Fig. 1 (a-h) gives the temperature evolution of the pattern observed. In the paramagnetic range (T > 32 K) no scattering was seen (Fig.1a). Upon lowering temperature, the ring of scattering intensity appears that is typical for the critical fluctuations of the spiral structure with the randomly oriented wavevector $\mathbf{k}_f$. Two spots on the left and right sides of the ring arise at the temperature $T \approx 31.5$ K (Fig. 1 b). The wavevectors $\pm \mathbf{k}_c$ of this newly arising structure is parallel to the applied magnetic field and one concludes that they must be ascribed to the conical spin structure. These two peaks become stronger upon further lowering of the temperature. Additionally two more Bragg spots appear on the top and bottom of the intensity ring at aT = 30 K (Fig. 1c). The latter are ascribed to the A-phase as two of six spots visible in this experimental geometry. The intensity of the spots with $\mathbf{k}_h \perp \mathbf{H}$ jumps up at $T = T_C = 29.0$ K, being much larger than that of the other two spots with $\mathbf{k}_c \mid\mid \mathbf{H}$ (Fig. 1 d). We conclude that the A-phase dominates at the conical phase in the range from T_C down to $T = 28$ K (Fig. 1 (e,f)). Upon further lowering temperature below $T = 28$ K, the conical phase becomes favourable and the A-phase diminishes. Nevertheless, two spots with $\mathbf{k}_h \perp \mathbf{H}$ remain visible at $T = 27$ K and $T = 25$ K (Fig.1 (g,h)).

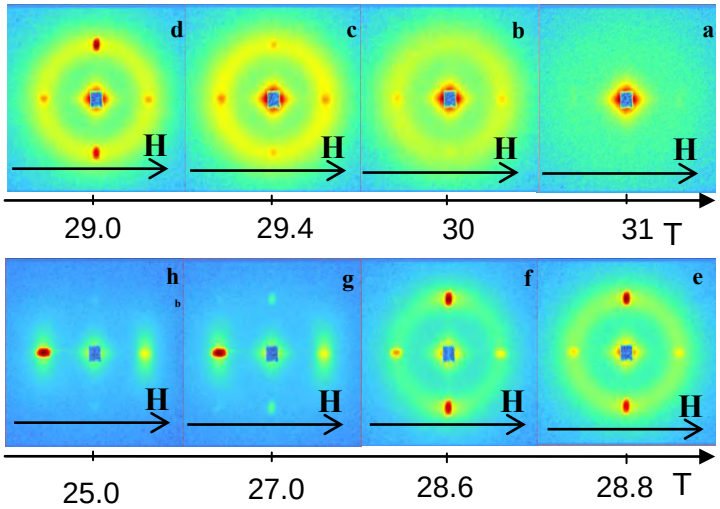

Fig.1 *Neutron scattering maps showing the temperature evolution of the magnetic system of MnSi at the field orientation* ***H*** *|| [11-1]* $\perp$***n*** *and H = 0.16 T.*

Upon field cooling at H = 0.16 T the conical phase appears at $T \sim T_{DM}$ and it coexists with the randomly oriented critical fluctuations of the plane spiral ($k_c \neq k_f$). The scattering function of the helix fluctuations is well described by the Lorentzian with the width κ_f at T_{DM} being roughly equal to k_c. The hexagonal A-phase structure is added to the existing ones upon further cooling at $T = T_k$, when $\kappa_f \approx k_c/2$ and $k_h \approx k_c$. The diffraction peaks for both structures are well described by Gaussian with the width, limited by the setup resolution function. The A-phase develops upon further cooling below T_C, while though co-existing conical phase remains suppressed. Below $T = 28$ K both the A-phase and critical fluctuations disappear and the conical phase is observed only.

We discuss our findings in terms of the stability of the A-phase and cone phase with respect to thermal energy estimated via the correlation length and energy of the critical fluctuations above T_C.

Session 7. Spin current and Hall effect in cubic ferromagnets without center of symmetry.

Chairman: Dr. Ted Monchesky

Coherent sliding dynamics and spin motive force driven by crossed magnetic fields in a chiral helimagnet

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One of the main problems in spintronics is a controllable motion of magnetic textures. There are two ways of to drive the motion, i.e. incoherent and coherent methods. The first one is typically realized by injecting a spin-polarized current into a sample [1]. On the other hand, the coherent method is realized in a magnetically ordered state by twisting the phase angle of the magnetic order parameter which directly couples to a magnetic field [2]. For example, one can use a rotating magnetic field, which is applied to one end of the sample and is strong enough to orient the magnetization parallel to it. Because of the stiffness of the spin system, the spin rotation at one end is transmitted to the other end of the sample, which is not subject to the direct effect of the rotating magnetic field. Transmission of the torque through the sample presents a spin current.

The incoherent current injection method to drive the sliding has already been proposed by us in Ref.[3]. In our recent paper [4] we proposed that chiral helimagnets are promising candidates to realize the coherent method. In particularly, we demonstrated that the chiral soliton lattice in a chiral helimagnet exhibits a sliding motion when a time-dependent magnetic field is applied parallel to the helical axis, in addition to a static field perpendicular to the helical axis. As it has been pointed out in Ref. [5], once the sliding is triggered, the soliton lattice maintains its persistent motion assisted by a generation of inertial mass. Another observable consequence of the coherent motion is an appearance of the spin motive force (SMF) [6], when the time dependence of the longitudinal magnetic field manifests itself in the temporal regime of the SMF. As a remarkable feature, we note that the chiral soliton lattice is a macroscopically ordered object, which contains macroscopic amounts of magnetic solitons (kinks). Due to this very large number of the solitons, the SMF is expected to be strongly amplified as compared with the SMF caused by a single magnetic domain wall in a ferromagnet. Numerical estimations show that the SMF reaches the order of millivolts that makes chiral magnetic crystals to be extremely promising for spintronic applications.

References

[1] I. Žutić , J. Fabian, and S. Das. Sarma, *Rev. Mod. Phys.* **76**, 323 (2004)
[2] E. B. Sonin, *Adv. Phys.* **59**, 181 (2010)
[3] J. I. Kishine, I. V. Proskurin, and A. S. Ovchinnikov, *Phys. Rev. B* **82**, 064407 (2010)
[4] J. Kishine, I.G. Bostrem, A.S. Ovchinnikov, Vl.E. Sinitsyn, *Phys. Rev. B* **86**, 214426 (2012)
[5] I. G. Bostrem, J. I. Kishine, and A. S. Ovchinnikov, *Phys. Rev. B* **77**, 132405 (2008); *ibid.* **78**, 064425 (2008)
[6] S. E. Barnes and S. Maekawa, *Phys. Rev. Lett.* **98**, 246601 (2007)

Unwinding of a skyrmion lattice by magnetic monopoles

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Skyrmion lattices are regular arrangements of magnetic whirls that exist in a wide range of chiral magnets [1]. Being characterized by a topological winding number, they cannot be created or destroyed by smooth rearrangements of the direction of the local magnetization. Using magnetic force microscopy we tracked changes of the magnetic structure on the surface of a bulk crystal of $Fe_{0.5}$ $Co_{0.5}$ Si as the skyrmion crystal is destroyed by reduction of the external magnetic field. Our study reveals that skyrmions vanish by a coalescence forming elongated structures indicating a change in topology.

Numerical simulations and neutron scattering data suggest that the same process also governs the transition in the bulk of the material. We find that changes of topology are thereby controlled by singular magnetic point defects, quantized magnetic monopoles and antimonopoles, providing sources and sinks of one flux quantum of emergent magnetic flux, respectively. During the phase transition, these monopoles act like the slider of a zipper combining and separating skyrmions.

In contrast to other magnetic monopoles that have been proposed in condensed-matter systems, these monopoles are the sources of the *emergent* magnetic field and follow Dirac's quantization condition for monopoles, i.e. they carry exactly one quantum of *emergent* flux. In other systems like e.g. spin-ice [2], the monopoles are sources of the *real* magnetic field but they are not quantized since their magnetic charge depends on microscopic details.

References

[1] S. Mühlbauer, B. Binz, F. Joenitz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, P.Böni, *Science* **13,** 915-919 (2009)
[2] C. Castelnovo, R. Moessner and S. L. Sondhi, *Nature* ***451****,* 42-45 (2008)

Emergent electrodynamics of skyrmions in a chiral magnet

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A Skyrmion crystal – a lattice of topologically stable magnetic whirls – can be stabilized in chiral magnets in a finite magnetic field range, and it has been identified so far in several metallic compounds like MnSi and $Fe_{1-x}Co_xSi$. Such magnetic skyrmions couple efficiently to spin-currents resulting in observable spintronic phenomena in a bulk material at low current densities of order 10^6 A/m^2. A spin-current can induce a finite spatial rotation of the skyrmion lattice [1], which can be understood as a double-transfer of angular momentum: in addition to the usual spin-transfer torque, angular momentum is transferred from the magnetic texture to the ionic crystal lattice giving rise to a mechanical torque resulting in a rotation of the skyrmion lattice. In addition, a moving skyrmion lattice leads to artificial electric and magnetic fields that act on the electrons and which were recently detected by Hall effect measurements [2]. As the electron spin constantly adapts to the skyrmion texture, its orbital motion experiences an artificial magnetic field of one flux quantum per skyrmion. If the applied electric current exceeds a threshold value, the depinning of skyrmions results in a moving magnetic texture that induces an artificial electric field via Farady's law of induction. The resulting emergent artificial electrodynamics promises to become an interesting playground for novel spintronic phenomena.

References

[1] F. Jonietz, S. Mühlbauer, C. Pfleiderer, A. Neubauer, W. Münzer, A. Bauer, T. Adams, R. Georgii, P. Böni, R. A. Duine, K. Everschor, M. Garst, and A. Rosch, Science **330**, 1648 (2010)
[2] T. Schulz, R. Ritz, A. Bauer, M. Halder, M. Wagner, C. Franz, C. Pfleiderer, K. Everschor, M. Garst, and A. Rosch, Nature Physics **8**, 301 (2012)

Giant generic topological Hall resistivity and formation of a topological non-Fermi liquid in MnSi under pressure

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Fermi liquid theory provides a remarkably powerful framework for the description of the conduction electrons in metals and their ordering phenomena, such as superconductivity, ferromagnetism, and spin- and charge-density-wave order. A class of ordering phenomena of great interest concerns spin configurations that are topologically protected, that is, their topology can be destroyed only by forcing the average magnetization locally to zero. Examples of such configurations are hedgehogs (points at which all spins are either pointing inwards or outwards) and vortices. A central issue is to determine the nature of the metallic state in the presence of such topologically distinct spin textures.

Here we report a high-pressure magneto-transport and magnetisation study of the metallic state at the border of the skyrmion lattice in MnSi, which represents a new form of magnetic order composed of topologically non-trivial vortices. Tracking the role of sample quality, pressure transmitter and field and temperature history allows us to link the emergence of a giant topological Hall resistivity ~50 nΩcm to the skyrmion lattice phase at ambient pressure. We show that the remarkably large size of the topological Hall resistivity in the zero temperature limit must be generic and discuss various mechanisms which can lead to the much smaller signal at elevated temperatures observed at ambient pressure [1].

Moreover, when long-range magnetic order is suppressed under pressure, the key characteristic of the skyrmion lattice, that is, the topological Hall signal due to the emergent magnetic flux associated with the topological winding is unaffected in sign or magnitude and becomes an important characteristic of the metallic state. The regime of the topological Hall signal in temperature, pressure and magnetic field coincides thereby with the exceptionally extended regime of a pronounced non-Fermi-liquid resistivity. The observation of this topological Hall signal in the regime of the NFL resistivity suggests that spin correlations with non-trivial topological character may drive a generic breakdown of Fermi liquid theory [2].

References

[1] R. Ritz, M. Halder, C. Franz, A. Bauer, M. Wagner, R. Bamler, A. Rosch, and C. Pfleiderer, *Phys. Rev. B (in press)* (2013)
[2] R. Ritz, M. Halder, C. Franz, M. Wagner, A. Bauer, and C. Pfleiderer, *Nature (in press)* (2013)

Peculiarities of magnon spectrum in planar ferromagnets with a skyrmion

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We study the modification of magnons in a quantum Heisenberg ferromagnet, when the ground state is described by the single skyrmion configuration of spins. [1] In the absence of various stabilizing interactions [2] such skyrmion configuration is metastable and higher in classical energy, than the conventional ferromagnetic state. We perform the quasiclassical analysis of magnon dispersion, starting with the lattice Hamiltonian, then seeking the non-trivial configuration of average spins and performing 1/S expansion. In the usual ferromagnet the magnon dispersion is $E_k = Dk^2$ and magnon wave functions are plane waves. In the skyrmion configuration the magnons are described by Schroedinger equation with a quantum-well potential. We show, that there is one localized magnon state inside this quantum well, with the negative energy $E = -2.545\ Dr_0^{-2}$, where r_0 the skyrmion radius. It means that the skyrmion configuration is thermodynamically unstable, with small perturbations leading to Bose condensation of magnons at the lowest energy and the resulting collapse of the skyrmion. Such analysis of quantum fluctuations of skyrmion configuration was not done before, and our conclusions are in qualitative agreement with [3].

References

[1] X. Z. Yu *et al., Nature* **465**, 901 (2010)
[2] A. B. Butenko *et al., Phys. Rev. B* **80**, 134410 (2009)
[3] A. Abanov and V. L. Pokrovsky, *Phys. Rev. B* **58**, R8889 (1998)

Session 8. DM interaction in nanostructures at the surfaces and interfaces.

Chairman: Dr. Markus Garst

Magnetic nano-skyrmions and phase transitions in Fe monolayer on Ir(111)

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Previous experimental spin-polarized scanning tunneling microscopy studies of a hexagonal Fe monolayer deposited on Ir(111) substrate provided qualitative and quantitative data for the analysis of the ground state of the system [1]. Together with a theoretical model based on first-principles calculations, the ground state of Fe/Ir(111) had been identified as a topologically nontrivially modulated spin structure [1]. Moreover, first-principles calculations reveal a strong competition between different energy terms. In particular, due to strong hybridization of electronic states at the Fe-Ir interface, the ferromagnetic exchange interaction between nearest neighbors is relatively small and of comparable order of magnitude as other types of exchange interactions such as the *four-spin interaction* and Dzyaloshinskii-Moriya (DM) interaction.

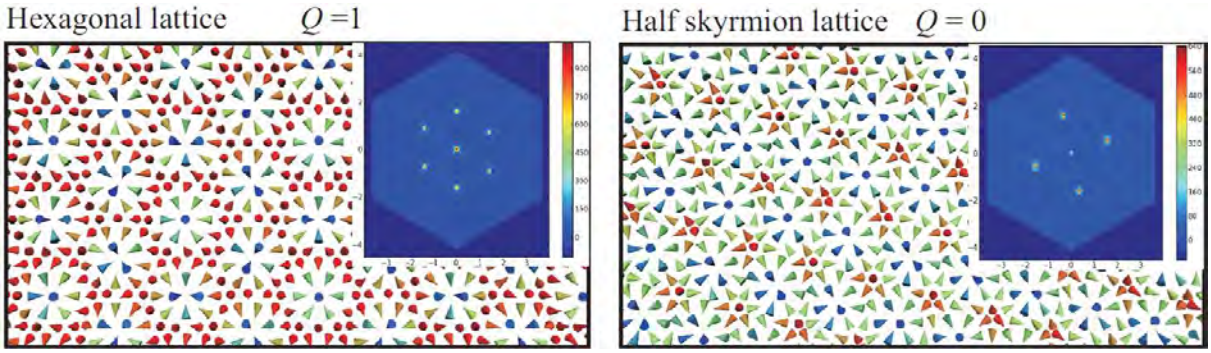

Fig. 1 *(left) Spin structure of the ground state of the system (T = 0 K) at high magnetic field – hexagonal lattice and (right) at zero magnetic field – half skyrmion lattice. Insets show corresponding Fourier transformation for z-component of magnetization for each state.*

The emergence of the DM type interaction in this system may be described to good approximation by the Fert-Levy mechanism [2], where interactions between Fe spins are arising from the spin-orbit scattering of the conduction electrons at nonmagnetic Ir atoms.

To investigate the in-field and temperature behavior of the system we perform Monte Carlo (MC) simulations in the frame of an extended Heisenberg model, which includes (i) long-ranged exchange interactions, (ii) the four-spin interaction, (iii) the antisymmetric Dzyaloshinskii-Moriya exchange, (iv) the biquadratic exchange, (v) an out-of-plane uniaxial anisotropy, and (vi) the Zeeman energy.

We use the common mixed phase MC algorithm for the system with strong hysteretic effects [3], as well as the Wang-Landau (WL) algorithm [4], which is known to be one of the most efficient algorithms to obtain the thermodynamic quantities as specific heat, magnetic susceptibility and free energy. One of the main features of this algorithm is that the random walker of the WL algorithm is not trapped by local energy minima, which is very important for a system with a complex energy landscape [4]. We discuss realizations of the methods and are comparing the results.

We present an exhaustive analysis of the ground state of the system based on energy balance and topology of the solutions. Due to the short periodicity of two-dimensional magnetic unit cell and discreetness induced by the underlying atomic lattice, a continuum approach counting for topological charge becomes ambiguous. We follow Berg und Lüscher [5], which is the most precise approach for

counting the topological charge on a discrete lattice. According to our analysis the ground state of Fe/Ir(111) is a staggered meron (half-skyrmion) lattice. Moreover, we predict the existence of a hexagonal lattice of skyrmions stabilized at high field and temperature (see Fig.1). We discuss in detail field- and temperature-induced transitions and compare our results with experiment.

Due to the non-trivial topologies of both magnetic lattices, the hexagonal lattice of skyrmions and of the lattice of half-skyrmions, the field- and temperature-induced transitions between them are characterized by an extremely strong hysteretic effect. In fact, such a transition may occur only in the immediate vicinity of the ordering temperature. When thermal fluctuations start to dominate, the system is able to overcome extremely high-energy barriers in both directions, while at low temperature the field-induced transition has always unidirectional character. We think that this effect may be translated into new ideas for possible applications of such systems in logic devises or sensors.

References

[1] S. Heinze, K. von Bergmann, M. Menzel, J. Brede, A. Kubetzka, R. Wiesendanger, G. Bihlmayer, and S. Blügel, *Nature Physics* **7**, 713 (2011)
[2] A. Fert and P.A. Levy, *Phys. Rev. Lett.* **44**, 1538 (1980)
[3] M. Creutz, L. Jacobs, and C. Rebbi, *Phys. Rev. D* **20**, 1915 (1979)
[4] C. Zhou, T. C. Schulthess, S. Torbrügge and D. P. Landau, *Phys. Rev. Lett.* **96**, 120201 (2006)
[5] B. Berg and M. Lüscher, *Nucl. Phys. B* **190**[FS3], 412 (1981)

First-principles study of topologically non-trivial spin structures at surfaces

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Recently, it has been discovered that the magnetic phase space of nanostructures at surfaces is tremendously enhanced due to the interplay of competing magnetic interactions. In particular, it has become apparent that the Dzyaloshinskii-Moriya (DM) interaction plays a key role for ultra-thin films, clusters, or atomic chains at surfaces. The DM interaction originates from spin-orbit coupling and can occur in every system with broken inversion symmetry such as surfaces. Surprisingly, it had not been taken into account for transition-metal films at surfaces until Bode et al. [1] demonstrated its relevance in such systems. The DM interaction prefers a canting of the spins of adjacent atoms and induces spin structures with a unique rotational sense. It can lead to spin spirals in ultra-thin films [1-3] as well as in atomic chains [4] on surfaces and can determine the rotational sense of domain walls in ferromagnetic nanowires [5].

Especially exciting are spin structures with non-trivial topology such as skyrmions. Recently, an atomic-scale magnetic skyrmion lattice has been revealed as the magnetic ground state of a monolayer Fe film on the (111) surface of Ir [6]. Here, we demonstrate that the magnetic properties of this system can be tuned by growing additional atomic overlayers of other transition-metals such as Rh, Ir, or Pd. We have performed first-principles calculations based on density functional theory (DFT) in order to determine the exchange interaction, DM interaction, and the magnetocrystalline anisotropy in these systems. The resulting extended Heisenberg model has been studied using Monte-Carlo simulations to investigate the phase diagram of our systems. Experimentally, Pd/Fe/Ir(111) has been studied using spin-polarized scanning tunneling microscopy [7] and single skyrmions have been observed upon applying an external magnetic field. We interpret these measurements based on our first-principles calculations.

References

[1] M. Bode *et al.*, *Nature* **447**, 190 (2007)
[2] P. Ferriani *et al*., *Phys. Rev. Lett.* **101**, 027201 (2008)
[3] Y. Yoshida *et al*., *Phys. Rev. Lett.* **108**, 087205 (2012)
[4] Menzel, M. *et al., Phys. Rev. Lett.* **108**, 197204 (2012)
[5] M. Heide *et al., Phys. Rev. B* **78**, 140403(R) (2008)
[6] Heinze, S. *et al Nature Physics*, **7**, 713 (2011)
[7] N. Romming, M. Menzel, Ch. Hanneken, J. E. Bickel, B. Wolter, K. von Bergmann, A. Kubetzka, and R. Wiesendanger (submitted)

Study of filed induced chirality in helix structure Ho/Y myltilayers

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The magnetic structures of the rare-earth metals result from the competition between the exchange and the crystal field interactions. The former are moderated by the conduction electrons and tend to favour magnetic structures which are incommensurate with the underlying crystal structure [1]. A few years ago we have demonstrated that Dy/Y magnetic multilayer structures (MMLs) possess a coherent spin helix with a preferable chirality induced by the magnetic field [1]. A magnetic field applied in the plane of the sample upon cooling below T_N is able to repopulate the otherwise equal population numbers for the left- and right-handed helixes. The experimental results strongly indicate that the chirality is caused by Dzyaloshinskii-Moriya interaction due to the lack of the symmetry inversion on the interfaces. Our choice of Ho superlattices was therefore made to see if Ho/Y superlattices behaved similarly to the Dy/Y superlattices previously studied.

The polarized neutron reflectometry is used to show that metal magnetic/nonmagnetic (Ho/Y) multilayer structures posses a coherent spin helix propagating through many Ho/Y bilayers. The samples of different thicknesses of Ho and Y layers were grown by molecular-beam-epitaxy techniques: [$Ho_{42Å}/Y_{30Å}$] (S1), [$Ho_{30Å}/Y_{15Å}$] (S2), [$Ho_{20Å}/Y_{30Å}$] (S3), [$Ho_{60Å}/Y_{30Å}$] (S4), [$Ho_{30Å}/Y_{30Å}$] (S5). We measured the chirality parameter $\gamma=(I^+ - I^-)/(I^+ + I^-)$ of the multilayers as a function of the temperature and magnetic field. This parameter is directly related to the imbalance between the left- and right-handed spiral, where $I^{+/-}$ is the integrated intensity of the helical peak with up (+) and down (-) neutrons. The chirality γ is equal to 0 for all samples cooled in zero field. The magnetic field of 1 T, applied in the plane of the sample upon cooling below T_N, induces non-zero chirality, which almost independent on the temperature for the samples S1, S2, S3. Opposite to it the field does not induce any chirality for samples S4 and S5. We assume that the non-zero chirality is only detected in the samples where the field is able to couple to the uncompensated moments of the helix within the Ho layer. The experimental results are explained by presence of Dzyaloshinskii-Moriya interaction caused by the lack of the symmetry inversion on the interfaces.

References

[1] Jensen J et al., Rare Earth Magnetism. Structures and Excitations; Oxford: *Oxford University Press* (1991)
[2] S. V. Grigoriev et al., *Phys.Rev. B* **82**, 195432 (2010)

Session 9. Frustration in the magnetic nanostructures.

Chairman: Dr. Dieter Lott

Magnetic states and ferromagnetic resonance in geometrically frustrated multilayer artificial spin ice on triangular gratings

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We present the results of theoretical studies of the magnetic states, peculiarities of magnetization reversal processes and ferromagnetic resonance in geometrically frustrated arrays of ferromagnetic nanoparticles. In a literature such objects are called as "artificial spin ice" [1-3]. The increased interest to these systems is stimulated by promising applications for the development of magnetic logic and tunable microwave filters [4-6]. In present work we consider the multilayer nanostacks consisting of ferromagnetic elliptical disks with 100 × 200 × 20 nm sizes separated by nonmagnetic spacers and ordered on the lattices with triangular symmetry (Fig. 1).

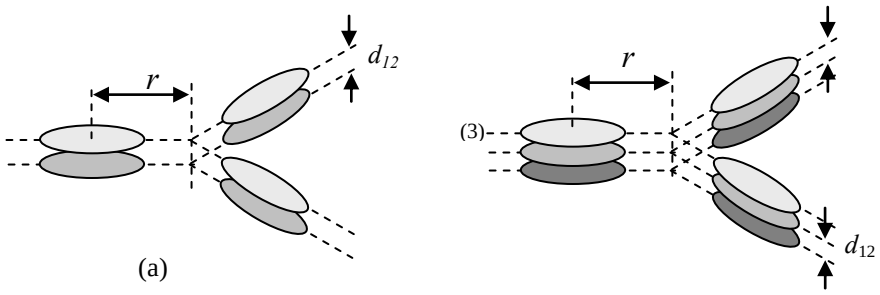

Fig. 1 *Schematic images of two-layer (a) and three-layer (b) stacks ordered on triangular grating.*

On the base of simple model of anisotropic point dipoles (with anisotropy corresponding to the shape anisotropy for the elliptical disks) and micromagnetic simulation of multilayer stacks of elliptical nanodisks we have analyzed a set of stable spatial configurations of the magnetic moments, which are realized in such systems in an external magnetic field. The effects of intralayer and interlayer interaction were studied.

We performed the calculations of the ferromagnetic resonance (FMR) spectra for the different states of multilayer systems. Spectrum of eigenfrequencies for the interacting particles is determined by magnetostatic interaction and essentially depends on the spatial configuration of the magnetic moments. This allows changing the magnetic state of the array significantly change the spectrum of FMR. Normalized FMR frequencies depending on the distance between the layers for different configurations of the magnetic moments of the particles in arrays consisting of two- and three-layer particles are shown in Fig. 2.

Magnetostatic interaction leads to the frequencies splitting and significant changing in the FMR spectrum [7]. The nonmonotonic dependencies observed in Fig. 3 are connected with the competition of the intralayer and interlayer interactions. Besides, it is clear seen that the magnetization reversal of arrays from a state with ferromagnetic ordering of layers in the state with antiferromagnetic ordering is accompanied by changing in the FMR spectrum and shifting to higher frequencies.

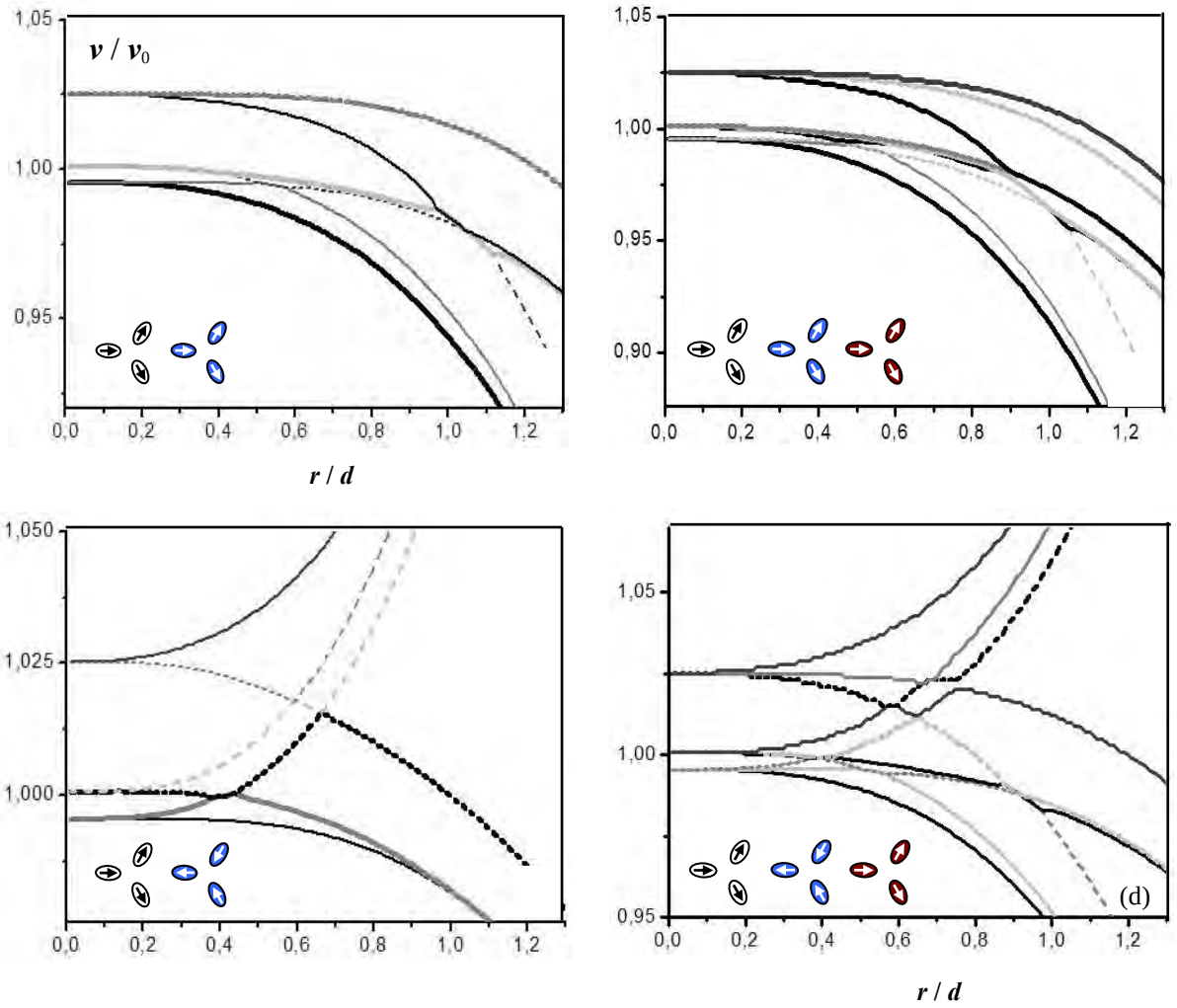

Fig. 2 *The dependencies of normalized FMR frequencies for the array of two- (a,b) and three-layer (c,d) nanodisks (100 × 200 × 20 nm for each disk) on the distance between the layers d (d_{12}=d_{23}) for r = 150 nm. (a) and (c) are for the case of ferromagnetic interlayer ordering, (b) and (d) are for antiferromagnetic interlayer ordering.*

This work was supported by Russian Foundation for Basic Research; Programs of Russian Academy of Science ("Fundamentals of technology of nanostructures and nanomaterials," "Spin phenomena in solid nanostructures and spintronics", "Quantum macro-physics") and The Ministry of Education and Science of The Russian Federation

References

[1] R.F. Wang, C. Nisoli, R.S. Freitas, J. Li, W. McConville, B.J. Cooley, M.S. Lund, N. Samarth, C. Leighton, V.H. Crespi, P. Schiffer, *Nature*, **439**, 303 (2006)
[2] C. Nisoli, R. Wang, J. Li, W.F. McConville, P.E. Lammert, P. Schiffer, V.H. Crespi, *Phys. Rev. Lett.*, **98**, 217203 (2007)
[3] A. Westphalen, A. Schumann, A. Remhof, H. Zabel, M. Karolak, B. Baxevanis, E.Y. Vedmedenko, T. Last, U. Kunze, T. Eimuller, *Phys. Rev. B*, **77**, 174407 (2008)
[4] A. Imre, G. Csaba, L. Ji, A. Orlov, G. H. Bernstein, W. Porod, *Science* **311**, 205 (2006)
[5] H. Zhang, A. Hoffmann, R. Divan, and P. Wang, *Appl. Phys. Lett.*, **95**, 232503 (2009)
[6] N. Kuhlmann, A. Vogel, and G. Meier, *Phys. Rev. B*, **85**, 014410 (2012)
[7] V.L. Mironov, O.L. Ermolaeva, E.V. Skorokhodov, and J.A. Blackman, *Bulletin of the Russian Academy of Sciences, Physics*, **77**(1), 32 (2013)

The «ice-rule» and magnetization in the inverse opal-like structure

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We study magnetic properties of the three-dimensional ferromagnetic cobalt net ordered in the face centered cubic (fcc) structure – inverse opal-like structure (IOLS). The Co IOLS was prepared using a templating technique in three steps. First, polystyrene spheres with diameter of 540 nm form on the conductive substrate a colloidal crystal film (template) with fcc structure with the area of 1 cm^2 and the thickness of 14 μm. Then, electrochemical crystallization of cobalt in the voids between the spheres was carried out. Finally, microspheres were dissolved in toluene. [1,2].

The basic element of this structure is a complex of quasitetrahedron, quasicube and another quasiterahedron connected along the spatial diagonal of the cube (<111>-type). The idealized element is presented in Fig. 1a. In reality the faces of these tetrahedra and cube are concave, since they were formed by the surface of the spherical particles.

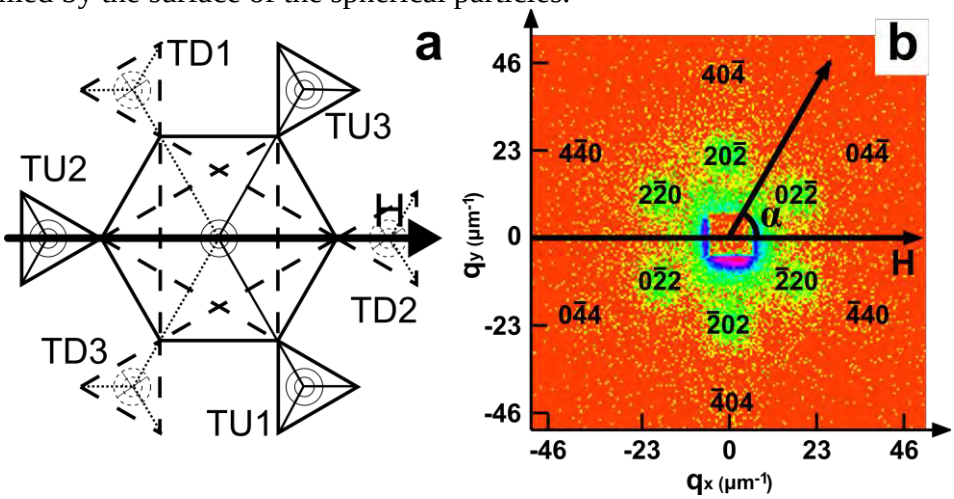

Fig. 1 *Projection of idealized basic element of IOLS on (111) plane with attached tetrahedra of four such neighbouring elements (a) and neutron diffraction patterns for Co IOLS in field H = 294 mT applied along* $[\bar{1}2\bar{1}]$ *axis. The Miller indexes of the reflections corresponds to the fcc structure with the lattice constant of* $a_0 = 0.76 \pm 0.01$ *μm.*

The SANS experiments were performed at the SANS-2 setup in Geesthacht (Germany). A neutron beam with a wavelength λ = 1.2 nm, and a divergence η = 1.5 mrad was used. The scattered neutrons were detected by a PS detector set at a distance 21.5 meters from the sample. The Q-range was covered from 5 to 50 μm^{-1} with a step of 0.5 μm^{-1}. Cobalt IOLS film was oriented perpendicularly to the incident beam. In this position the [111] axis of the fcc structure with the 3-fold symmetry was oriented parallel to the incident beam. The recorded neutron diffraction patterns consist of several clearly resolved sets of hexagonally arranged reflexes (Fig. 1b). The external magnetic field H up to 1.2 T was applied perpendicular to the incident beam and along the $[\bar{1}2\bar{1}]$ axis of the IOLS.

SANS experiments have revealed a magnetization distribution coinciding with the spatial net of IOLS. We have constructed the model of this distribution, using the «ice-rule» concept [3,4].

Our model requires the magnetic flux conservation in tetrahedra and cubes of IOLS to minimize the magnetic energy of the system. We compared the experimental SANS data with the scattering intensity predicted from the model and found a satisfactory agreement. Thus we show that the magnetic system of IOLS is determined by the generalized «ice-rule» model and results in the macroscopically measured component of magnetization perpendicular to the applied magnetic field. The local distribution of the magnetization at the different stages of the remagnetization process is presented in Fig. 2. Each stage is characterized by the critical magnetic field H_{ci} corresponding to the remagnetization of the different elements of the basic unit cell of the magnetic net of the IOLS.

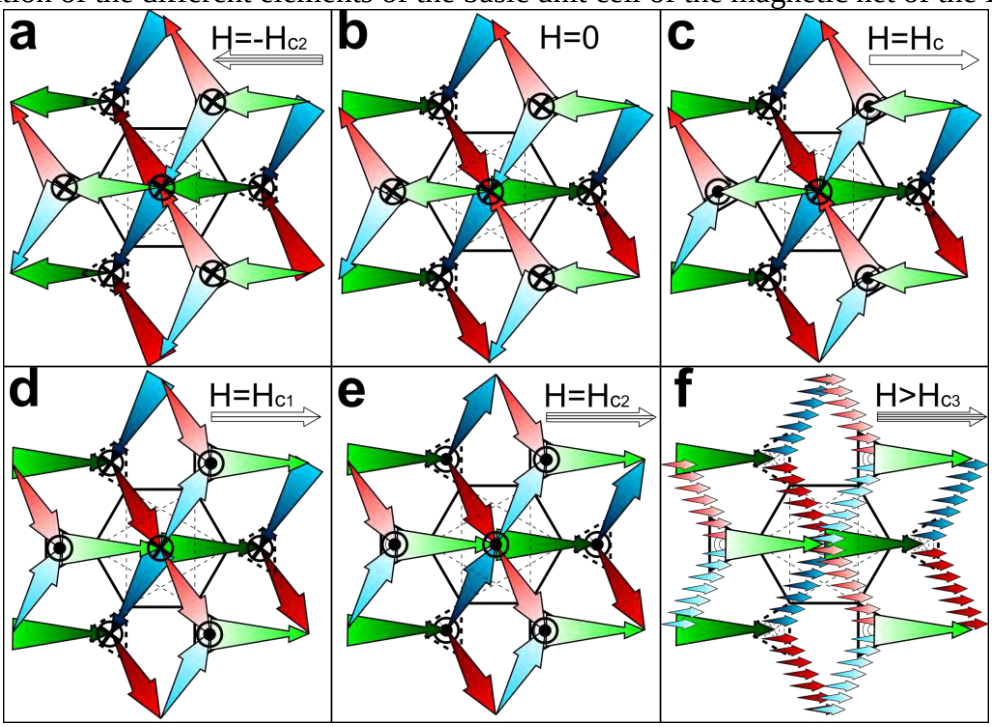

Fig. 2 *Magnetization distribution in IOLS for the different state of the remagnetization process (a-f). The Ising-like magnetic moments directed along the <111> axes are shown by arrows in (220), (022) and (202) planes. Those of them, which lie in higher plane are lighter.*

Work was supported by the DAAD program «Dmitry Mendeleev» 2012 and RFBR grant № ofi-m 12-02-12066/12.

References

[1] S. V. Grigoriev, K. S. Napolskii, N. A. Grigoryeva, A. V. Vasilieva, A. A. Mistonov, D. Yu. Chernyshov, A. V. Petukhov, D. V. Belov, A. A. Eliseev, A. V. Lukashin, Yu. D. Tretyakov, A. S. Sinitskii, H. Eckerlebe, *Phys.Rev. B*, v. 79, 045123 (2009)

[2] N. A. Grigoryeva, A. A. Mistonov, K. S. Napolskii, N. A. Sapoletova, A. A. Eliseev, W. Bouwman, D. V. Byelov, A. V. Petukhov, D. Yu. Chernyshov, H. Eckerlebe, A. V. Vasilieva, and S. V. Grigoriev, *Phys.Rev. B*, v. 84, 064405 (2011)

[3] M. J. Harris, S. T. Bramwell, D. F. McMorrow, T. Zeiske and K. W. Godfrey, *Phys. Rev. Lett.*, v. 79, 2554 (1997)

[4] A.P. Ramirez, A. Hayashi, R.J. Cava, R Siddharthan, and B.S. Shastry, *Nature*, v. 399, 333 (1999)

Antivortex state in cross-like nanomagnets

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The realization of isolated antivortex state (topological counterpart of a magnetic vortex) in ferromagnetic nanostructures is a challenging task [1 - 3] connected with observation of topological Hall effect and study of spin dynamics in microwave fields. Since the antivortex (AV) has a "magnetic charge" the implementation of such state is difficult because of the excess magnetostatic energy. In practice the AV is usually realized as the part of multivortex states [3]. To realize the isolated antivortex, we fabricated asymmetrical cross-like nanoislands (SEM image is shown in Fig. 1a). The magnetic states were investigated by magnetic force microscopy (MFM) methods. The AV state was generated by magnetization reversal in several stages. At the first stage, a strong magnetic field was applied along the nonsymmetrical diagonal of the crosses and quasiuniform magnetization was formed (Fig. 1b). Then, under the action of a certain reversed magnetic field H with magnitude $H_1 < H < H_2$ (H_1 and H_2 are the coercivity of bulbous and tapered ends, respectively), we observed the formation AV states in all crosses (Fig. 3c) [4].

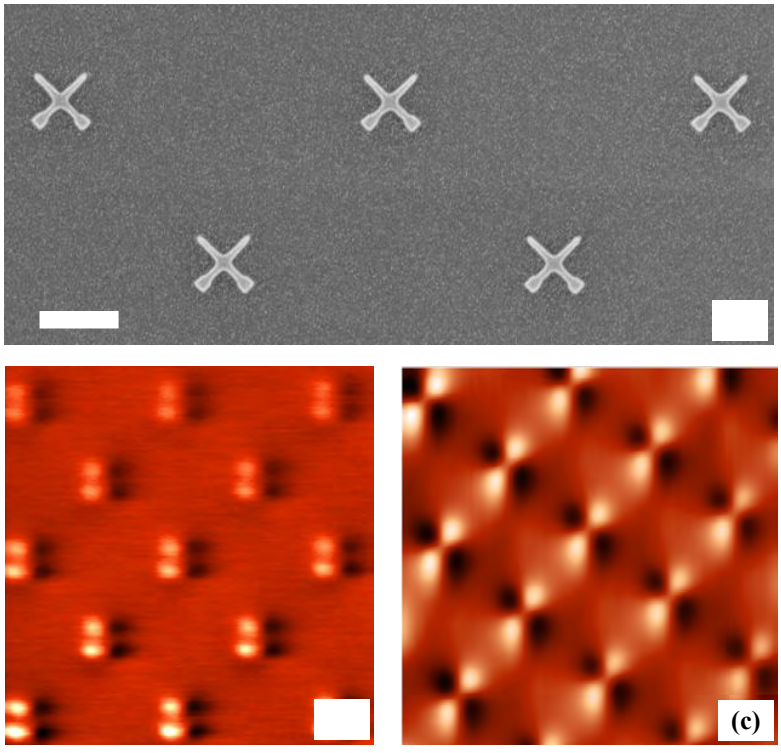

Fig. 1 *(a) is the SEM image of asymmetric Co nanocrosses. The white scale bar is 1 μm. (b) is the MFM image of crosses in the quasiuniform state. (c) is the MFM image of crosses in the antivortex state. MFM frame size is 12×12 μm.*

We carried out also the experiments on the magnetization reversal of symmetric cross-shaped nanoislands under the action of the nonuniform field of the MFM probe to investigate the processes of the formation of AV state [5]. We employed a two-stage process, in which, first, the magnetic state of cross-like nanoisland was transformed, by means of the local scanning, from the quasi-

homogeneous state of type A (Fig. 4 a,b) into a quasi-uniform state of type B (Fig. 4 c,d) and then into the antivortex state (Fig. 4 e,f).

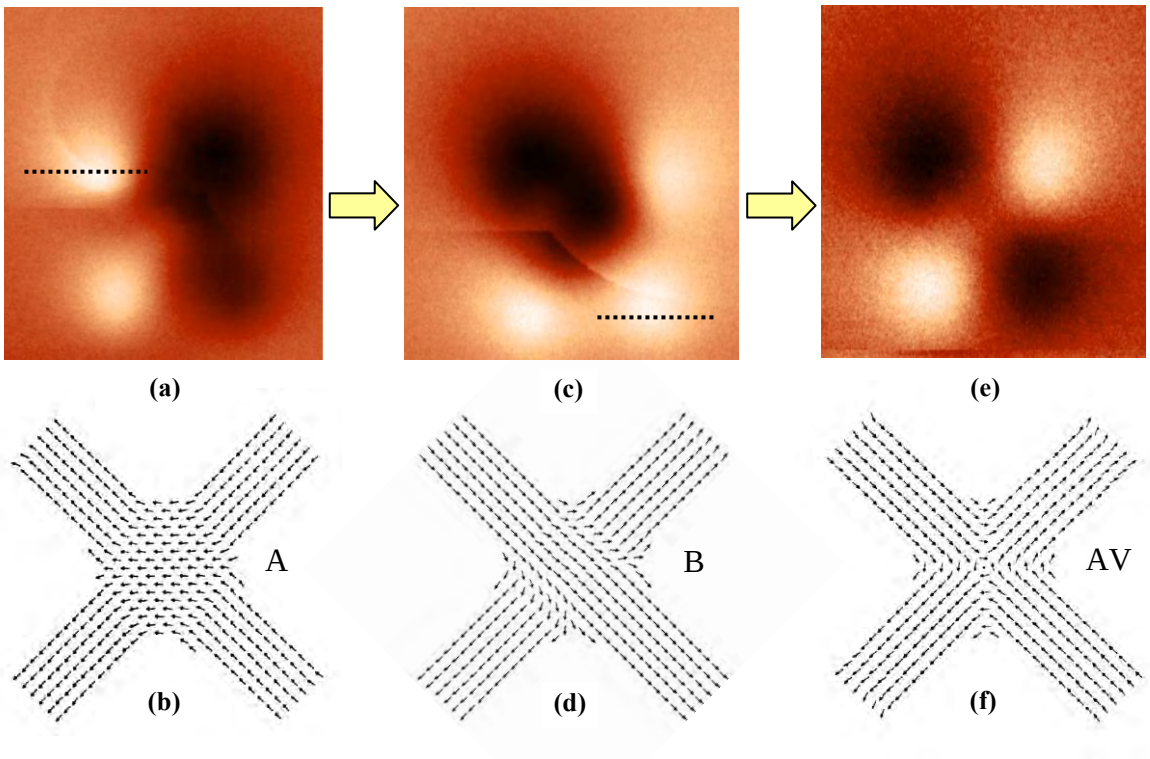

Fig. 2 *MFM images and corresponding magnetization distributions for probe induced transitions in cross-like particle. (b) is quasi-homogeneous state of type A; (d) is quasi-homogeneous state of type B; (f) is the antivortex state. The positions of scanning lines are indicated by dashed lines in MFM images.*

The applications of cross-like nanomagnets for the study of spin dependent transport and observation of topological Hall effect are discussed.

The authors are very thankful to I.A. Nefedov, I.M. Shereshevsky I.A. Karetnikova for the assistance in micromagnetic simulations and to A.Yu. Klimov and V.V. Rogov for patterned samples preparation.

This work was supported by Russian Foundation for Basic Research; Programs of Russian Academy of Science ("Fundamentals of technology of nanostructures and nanomaterials," "Spin phenomena in solid nanostructures and spintronics", "Quantum macro-physics") and The Ministry of Education and Science of The Russian Federation

References

[1] S. Gliga, M. Yan, R. Hertel, C. M. Schneider, *Phys. Rev. B*, **77**, 060404R, (2008)
[2] H. Wang and C.E. Campbell, *Phys. Rev. B*, **76**, 220407 (2007)
[3] K. Shigeto, T. Okuno, K. Mibu, T. Shinjo, T. Ono, *Appl. Phys. Lett*., **80**, 4190, (2002)
[4] V.L. Mironov, O.L. Ermolaeva, S.A. Gusev et al., *Phys. Rev. B*, **81**, 094436 (2010)
[5] V.L. Mironov, A.A. Fraerman, et al., *The Phys. Met. Metallogr.*, **110** (7), 708 (2010)

Matching domain-wall configuration and spin-orbit torques for efficient domain-wall motion

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In our numerical study [1], we identify the best conditions for efficient domain-wall motion and magnetization switching by spin-orbit torques originating from the spin Hall effect or Rashba effect. We demonstrate that the effect depends critically on the domain-wall configuration, the current injection scheme, and the symmetry of the spin-orbit torque. The best identified configuration corresponds to a N´eel wall driven by the spin Hall effect in a narrow strip with perpendicular magnetic anisotropy. In this case, the domain-wall velocity can be a factor of 10 larger than that for the conventional current-in-plane spin-transfer torque.

This work is partly supported by the ANR agency (Grant "ESPERADO" 11-BS10-008 and SpinHall), the RFBR (Grant No. 11-02-91067), and CNRS PICS Russie (Grant No.57432011).

References

[1] A.V.Khvalkovskiy, V.Cros, D.Apalkov, V.Nikitin1, M.Krounbi, K.A.Zvezdin, A. Anane, J.Grollier, and A. Fert, *Physical Review* B 87, 020402(R) (2013)

POSTER SESSION

Surface- and defect-induced Dzyaloshinskii-Moriya interactions: influence on vortex states in magnetic nanodots

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Structural defects in magnetic crystalline materials may locally change magnetic properties and can significantly influence the behavior of magnetic nanostructures. E.g., surface-induced Dzyaloshinskii-Moriya interactions can stabilize long-periodic spiral states [1] and cause formation of two-dimensional Skyrmionic textures [2]. Near lattice defects, the spin-orbit interactions induce local Dzyaloshinskii-Moriya exchange and cause effective anisotropies, which can result in spin canting [3].

Vortex states in magnetic nanodisks provide the simplest example of a handed magnetization structure, where effects of the chiral couplings may become noticeable. Within the usual micromagnetic description the shape and size of the vortices are determined by the competition between the exchange and stray-field energy. In particular, the vortices with different chirality are degenerate: the four possible vortex ground states differentiated by their handedness and polarity all have the same energy. However, these studies did not take into account the induced Dzyaloshinskii-Moriya interactions, which should generically exist in these systems due to broken mirror symmetry by the surface. As the vortex states are chiral themselves, the effect of the chiral Dzyaloshinskii-Moriya interactions is subtle: in the presence of Dzyaloshinskii-Moriya couplings the chiral degeneracy of the left- and right-handed vortices is lifted. The different chiral versions of the vortex states are shown to display strong dependencies on the materials properties of such nanodisks. Within a micromagnetic model for these effects, numerical calculations of the shape, size, and stability of the vortices in equilibrium as functions of magnetic field and the material and geometrical parameters provide a general analysis of the influence of the broken mirror symmetry caused by the surface/interfaces on their properties [4]. The Dzyaloshinskii-Moriya interactions impose differences in the energies and sizes of vortices with different chirality: these couplings can considerably increase sizes of vortices with one sense of rotation and suppress vortices with opposite sense of rotation. Numerical calculations show that vortices with different chirality have not only different energies and sizes, but also their magnetic structures differ. In case of chirality unfavourable with respect to the chiral Dzyaloshinskii-Moriya couplings, the vortex core consists of a narrow internal part and an adjacent ring with a reverse magnetization rotation. Obtained results for sizes and total perpendicular magnetization for vortices with opposite chirality may be used for experimental determination of strength of surface/interfaces-induced Dzyaloshinskii-Moriya interactions in ultrathin magnetic films/film elements.

Defects also break the local symmetry of the crystal structure and induce inhomogeneous magnetic couplings. Thus, defects can act as a source of additional local interactions. Depending on remaining symmetries, the induced magnetic couplings may consist of (i) local anisotropies and (ii) chiral magnetic Dzyaloshinskii-Moriya couplings. Developed micromagnetic description of defect-induced Dzyaloshinskii-Moriya interactions is the general formulation for chiral interactions caused by any kind of structural torsions [5]. As an application, vortex states in thin magnetic film elements are studied under influence of a screw dislocation in their center. This model is relevant for the general problem of chirality selection in magnetic nanostructures. It is demonstrated that defect-induced Dzyaloshinskii-Moriya interactions cause a similar chirality selection as surface-induced couplings. This effect could be observed also in thicker film elements or even in bulk single crystals under influence of screw dislocation lines. One growth mode of epitaxial films relies on screw dislocations and, alongside the surface-induced symmetry breaking, these defects can change

magnetic behavior of such films. In principle, the theoretically anticipated effects could be investigated in experiments on patterned epitaxial film elements.

References

[1] M. Bode, M. Heide, K. von Bergmann, P. Ferriani, S. Heinze, G. Bihlmayer, A. Kubetzka, O. Pietzsch, S. Blügel, and R. Wiesendanger, *Nature (London)* **447**, 190 (2007)
[2] S. Heinze, K. von Bergmann, M. Menzel, J. Brede, A. Kubetzka, R. Wiesendanger, G. Bihlmayer, and S. Blügel, *Nature Physics* **7**,713–718 (2011)
[3] A.B. Dichenko and V.V. Nikolayev, *J. Magn. Magn. Mater*. **53**, 71 (1985); A. Arrott, *J.Appl. Phys.* **34**, 1108 (1963); S. V. Maleev, *Phys. Uspekhi* **45**, 569 (2002)
[4] A.B. Butenko, A.A. Leonov, A.N. Bogdanov, and U.K. Rößler, *Phys. Rev. B* **80**, 134410 (2009); *J. Phys.: Conf. Ser.*, **200**, 042012 (2010)
[5] A.B. Butenko and U.K. Rößler, *EPJ Web of Conferences* **40**, 08006 (2013)

Hall effect of MnSi thin films

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The ferromagnetic compound MnSi exhibits a variety of different magnetic phases. The ground state of the system is a helical spin structure, which occurs due to the competition of ferromagnetic exchange with the Dzyaloshinskii-Moriya interaction. Furthermore, a conical and a parallel aligned state exist in certain magnetic field ranges. In a small field and temperature region close to the ordering temperature a skyrmion lattice phase occurs, which is known as the A-phase. In MnSi bulk crystals, a topological Hall resistivity for this A-phase has been observed, which amounts approximately $5*10^{-11}$ Ωm [1].

In thin MnSi films the skyrmionic phase is expected to be extended over larger regions of the phase diagram [2]. Therfore, we have performed Hall measurements on MBE-grown films. In these measurements an enhancement of the Hall effect is observed over a large temperature and magnetic field region which varies for films of different thickness. Our results are compared with Hall data published recently by Li *et al*. [3], who could show by Lorentz TEM the existence of skyrmion textures in the regime, where the enhanced Hall effect occurs.

References

[1] A. Neubauer, C. Pfleiderer, B. Binz, A. Rosch, R. Ritz, P. Niklowitz, and P. Böni, *Phys. Rev. Lett.* ***102***, 186602 (2009)
[2] A. B. Butenko, A. A. Leonov, U. K. Rößler and A. N. Bogdanov, *Phys. Rev. B* ***82***, 052403 (2010)
[3] Y. Li, N. Kanazawa, X. Z. Yu, A. Tsukazaki, M. Kawasaki, M. Ichikawa, X. F. Jin, F. Kagawa, and Y. Tokura, *Phys. Rev. Lett.* ***110***, 117202 (2013)

Fluctuation-driven first-order transition in the chiral magnet MnSi

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The chiral magnetic metal MnSi possesses various peculiar phases as a function of pressure and magnetic field. At high pressures, there is an extended phase that defies Fermi-liquid theory, and at a finite magnetic field a Skyrmion crystal phase was recently identified. Here, we concentrate on the temperature range close to the magnetic transition temperature T_c at ambient pressure, and we demonstrate that a series of unusual features can be explained in terms of strongly interacting chiral fluctuations [1]. We discuss theoretically and experimentally that interactions lead to strong renormalization effects resulting in a characteristic crossover temperature $T^* > T_c$ where the susceptibility shows a turning point and the specific heat a crossing point, also known as Vollhardt invariance. More importantly, the singular interactions drive the chiral transition first-order in agreement with Brazovskii-theory. Experimentally this is reflected in a sharp peak in the specific heat and small discontinuous jump in the temperature dependence of the helimagnetic Bragg peak as measured in small angle neutron scattering. In the presence of a magnetic field the chiral paramagnetic fluctuations get quenched so that at high fields the transition is of second order. This implies the presence of a fluctuation-induced tricritical point, which we investigated with the help of high-resolution specific heat measurements [2]. Our considerations relies on the limit of weak spin-orbit coupling and are based on basic symmetry principles so that we expect them to be applicable to a wider range of chiral magnets including $Fe_{1-x}Co_xSi$, MnGe, FeGe and the insulator Cu_2OSeO_3.

References

[1] M. Janoschek, M. Garst, A. Bauer, P. Krautscheid, R. Georgii, P. Böni and C. Pfleiderer, *Phys. Rev. B* **87**, 134407 (2013)

Long-range and short-range magnetic order in a quantum critical model of $Mn_{1-x}Fe_xSi$

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A specific feature of quantum helimagnets consists in forming of the chiral spin liquid (CSL) magnetic phases characterized by short-range order [1]. These materials can be driven into CSL phase either by weakening of the electron-electron interactions [2] or by disorder effects [3]. In the present work we consider a model, where magnetic phase with short-range order is controlled by characteristic lengths describing classical (R_{f1}) and quantum (R_{f2}) fluctuations. The short-range magnetic order phase develops when fluctuations of the order parameter in paramagnetic (P) phase (chiral gas [1]) freeze due to the condition $R_{f1,2}=R_s$ (R_s is some characteristic length in the considered material). The disorder effects may be taken into account by supposition that R_s is given by correlation length R_c, so that

$$R_{f1}=\frac{a_1}{[1-T/T_c(x)]^{\delta}};\ R_{f2}=a_2\frac{T_0}{T};$$

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

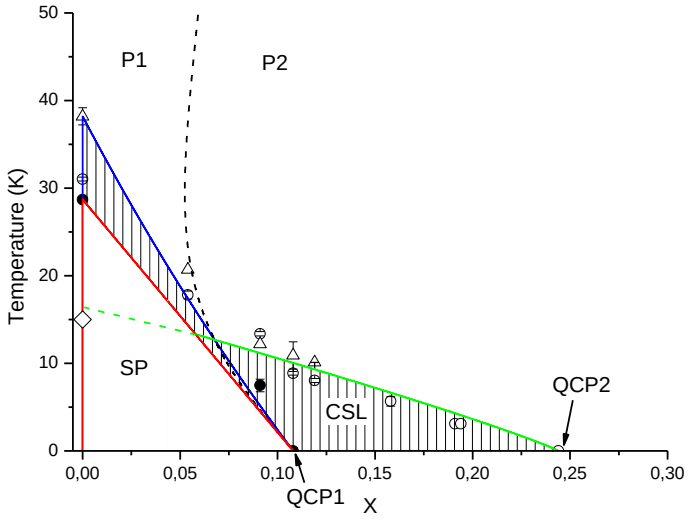

Fig. 1. Magnetic phase diagram of $Mn_{1-x}Fe_xSi$ solid solutions. Points denote experimental data; lines are theoretical calculations. The phases with short-range magnetic order are shaded.

Here x denotes parameter, which determines quantum criticality. Nontrivial physical behavior can be obtained when critical point corresponding to change of the topology of the magnetic subsystem x_c does not coincide with the "underlying" critical point x^* at which transition temperature into the spiral phase (SP) with long-range order $T_c(x)$ turns to zero: $T_c(x^*)=0$. If $x^*<x_c$ the CSL "tail" is formed and a new crossover line dividing areas with dominating classical (P1) and quantum fluctuations (P2) appears in the paramagnetic phase (fig. 1). Using model equations (1) we have computed magnetic phase diagram of $Mn_{1-x}Fe_xSi$ solid solutions where driving parameter x is given by iron concentration. The calculations are in good agreement with the results of magnetic measurements (fig. 1), which show sequence of quantum critical points located at x^* (QCP1) and x_c (QCP2). We argue that presence of both classical and quantum fluctuations in $Mn_{1-x}Fe_xSi$ may be explained by specific concentration dependences of the exchange and Dzyaloshinskii-Moria (DM) interactions [4]. The suggested ansatz allows interpreting low temperature anomaly of magnetotransport data discovered in MnSi at T~15 K [5] by quantum fluctuations effect. The possible microscopic nature of the quantum phase transition at x^* between magnetic phase with long-range order (chiral solid [1]) and chiral spin liquid is discussed. When assuming RKKY mechanism (this supposition is made in [6,7]) it is natural to expect that change of the electron concentration will affect exchange energy J and tune quantum criticality. The

computation of the RKKY function in MnSi structure gives ferromagnetic nearest neighbor (nn) exchange (J_1) and next-nn (J_2) and third-nn (J_3) antiferromagnetic couplings, which obey relations $|J_1| > |J_2| \approx |J_3|$. This frustrated Heisenberg model *without* DM interaction was considered in [7] and it was shown that frustration itself forms spin spiral structures aligned along (110) direction. At the same time it is known [4] that DM interaction favors (111) direction of the spin spirals. Consequently competing between frustration and DM interaction may lead to loosing of the long-range magnetic order and formation of a liquid-like chiral state. Moreover, an estimate within RKKY mechanism gives for MnSi the ratio $|J_1|/|J_2| \approx 0.26$, which is very close to the critical value $|J_1|/|J_2| \approx 0.21 - 0.32$, which defines stability of the ferromagnetic phase in the frustrated model [7], and it is possible to expect that even relatively small variations of electron concentration may induce changes of magnetic structure in $Mn_{1-x}Fe_xSi$.

This work is supported by Program of RAS "Strongly correlated electrons" and by RFBR grant 13-02-00160.

References

[1] S.Tewari, D.Belitz, T.R.Kirkpatrick, *Phys. Rev. Lett.* **96**, 047207 (2006)
[2] F.Kruger, U.Karahasanovic, A.G.Green, *Phys. Rev. Lett.* **108**, 067003 (2012)
[3] T.Vojta, R.Sknepnek, *Phys. Rev. B* **64**, 052404 (2001)
[4] S.V.Grigoriev et al., *Phys. Rev. B* **79**, 144417 (2009)
[5] S.V.Demishev, et al., *Phys. Rev. B* **85**, 045131 (2012)
[6] 12. J.M.Hopkinson, H.Y.Kee, *Phys. Rev. B* **79**, 014421 (2009)
[7] J.M.Hopkinson, H.Y.Kee, *Phys. Rev. B* **75**, 064430 (2007)

Microscopic modeling of the S=1/2 Heisenberg ferrimagnet Cu_2OSeO_3

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Cu_2OSeO_3 is a $S = 1/2$ Heisenberg ferrimagnet with a sizable magnetoelectric coupling [1]. Recent experimental studies reported magnetic-field-induced emergence of skyrmions in this insulating material [2]. Based on extensive density functional theory (DFT) band structure calculations, we evaluate isotropic (Heisenberg) as well as anisotropic (Dzyaloshinskii-Moriya) magnetic exchange couplings.

Five relevant magnetic couplings form a complex, non-frustrated spin model, which can be described as a pyrochlore lattice of magnetic tetrahedra. A peculiar feature of this lattice is the alternation of "strong" tetrahedra (the constituent spins are strongly coupled) and "weak" tetrahedra.

Profiting from the separation of the energy scales, we develop an effective model, treating strong tetrahedra either as a classical $S = 1$ object or as a coherent quantum superposition of classical states. For the latter case, we find an excellent agreement with the quantum Monte Carlo simulations of the full model and the experimental magnetization as well as neutron diffraction data.

We demonstrate that the developed effective model can be further used to model the field-induced behavior, including the formation of skyrmions.

References

[1] J.-W. G. Bos, C. V. Colin, and T. T. M. Palstra, *Phys. Rev. B* ***78***, 094416 (2008)

[2] S. Seki, X. Z. Yu, S. Ishiwata, and Y. Tokura, *Science* **336**, 198 (2012)

Magnetoresistance and exchange interaction in $Mn_{1-x}Fe_xSi$

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Strongly correlated electron system MnSi is known for decades as an archetypal example of itinerant magnet with helicoidal ordering at $T_C = 29$ K [1]. The quantum criticality under high pressure [2], the formation of skyrmion state [3] and topological Hall effect observed below 0.6 T near T_C [4] are hot topics of modern studies of this material. However, recent experiments explain the features of electron spin resonance and magnetic scattering within Heisenberg localized magnetic moments model at $B > 2$ T [5,6] thus contradicting to the itinerant magnetism of MnSi.

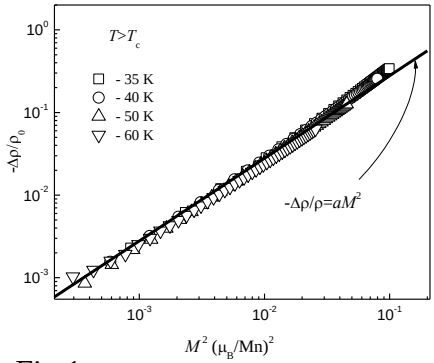

Fig.1 *The absolute values of negative magnetoresistance versus the squared magnetization: the universal relation in PM phase ($T > T_C$)*

The substitution of manganese with iron in $Mn_{1-x}Fe_xSi$ isostructural solid solutions suppresses transition temperature in helical state T_C which turns to zero at quantum critical point (QCP) x^*. The mechanism responsible for this process can be explained within either itinerant or localized picture of magnetic properties. Though neutron diffraction experiments showed that increase of x results in decrease of exchange interaction between localized magnetic moments (LMMs) J, which is expected turn to zero at the same point x^* as T_C, whereas asymmetric exchange (Dzyaloshinskii-Moria, DM) interaction magnitude D does not depend on sample composition so strongly and likely remains finite at x^* [7].

To understand the effect of substitution of manganese with iron on the magnetic properties of $Mn_{1-x}Fe_xSi$ solid solutions we have probed the paramagnetic (PM) and spin-polarized (SP) phases by resistivity, magnetoresistance and magnetization measurements in wide temperature range (2-300 K) in magnetic fields up to 8 T.

A universal relation between $\Delta\rho/\rho$ and M has been discovered in the PM phase of $Mn_{1-x}Fe_xSi$

$$\Delta\rho/\rho = -a_0 M^2. \quad (1)$$

Moreover, the breakdown of the relation (1) defines position of the boundary between the PM and SP phases [6]. In framework of Yosida s-d exchange model [8] for magnetic scattering of electrons on localized magnetic moments the coefficient a_0 allows estimating characteristics of the local exchange interaction between free charge carriers and LMMs. Assuming LMMs with spin S=1/2 and short-range nature of the scatters, the J_0/V_0 ratio, where J_0 stands for Fourier amplitudes of the exchange interaction between and V_0 is electrostatic scattering potential, can be computed [6].

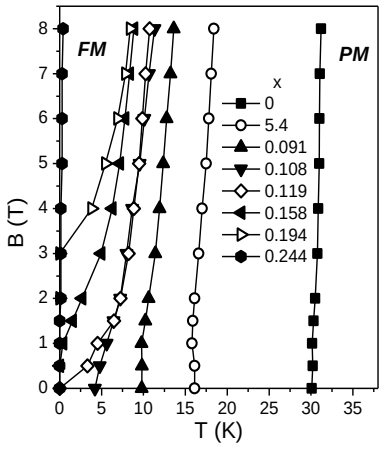

Fig.2 *Critical temperature T_C versus applied magnetic field for $Mn_{1-x}Fe_xSi$.*

The results of magnetoresistance analysis are presented in figs. 2,3. It is found (fig. 2) that the PM-SP phase boundary for $x < 0.11$ is almost vertical and shifts to lower temperatures with

increasing iron concentration. In the diapason $x > 0.11$ the phase boundary acquires a positive slope and exhibits a field induced transition to the ferromagnetic state for $0.16 < x < 0.2$.

The calculated J_0/V_0 ratio concentration dependence shows that the reduced amplitude of exchange interaction between free charge carriers and LMMs decreases monotonically with x, but, in contrast to exchange interaction between LMMs, this parameter does not turn to zero at the QCP x^* (fig. 3). It is clear to see that for $x > x^*$ the ratio J_0/V_0 is kept on the level $0.2 \div 0.3$ and thus the local exchange likely does not depend on the Fe concentration.

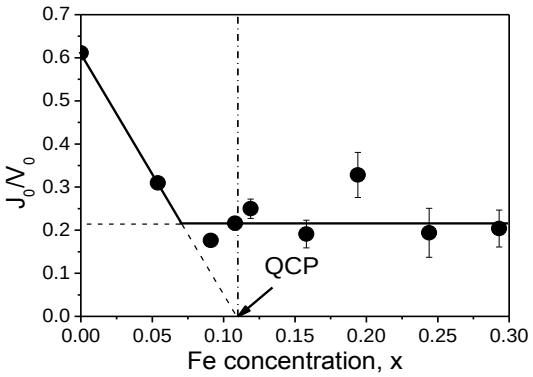

Fig.3 *J_0/V_0 ratio concentration dependence*

The aforementioned results strongly supports the applicability of the localized magnetic moments model proposed for MnSi [5, 6] to the case of $Mn_{1-x}Fe_xSi$ solid solutions for $x < 0.3$. The obtained J_0/V_0 ratio concentration dependence shows that interaction of the charge carriers with localized moments does not varnish at the QCP and stays constant above x^* indicating a possible influence of asymmetric exchange on magnetic scattering in this range of iron content.

This work was supported by The Programme of Russian Academy of Sciences "Strongly correlated electrons" and by RFBR grant 13-02-00160.

References

[1] T. Moriya *Spin fluctuations in itinerant electron magnetism*, Springer-Verlag, 1985
[2] D. Belitz et al., *Phys. Rev. Lett.* ***94***, 247205 (2005)
[3] A. Tonomura et al., *Nano Lett.* ***12***, 1673 (2012)
[4] A. Neubauer et al., *Phys. Rev. Lett.* ***102***, 186602 (2009)
[5] S.V. Demishev et al., *JETP Letters* ***93***, 231 (2011)
[6] S.V. Demishev et al., *Phys. Rev. B* ***85***, 045131 (2012)
[7] S.V. Grigoriev et al., *Phys. Rev. B* ***79***, 144417 (2009)
[8] K.Yosida, *Phys. Rev.* ***107***, 396 (1957)

Coherent sliding dynamics and spin motive force driven by crossed magnetic fields in a chiral helimagnet

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One of the main problems in spintronics is a controllable motion of magnetic textures. There are two ways of to drive the motion, i.e. incoherent and coherent methods. The first one is typically realized by injecting a spin-polarized current into a sample [1]. On the other hand, the coherent method is realized in a magnetically ordered state by twisting the phase angle of the magnetic order parameter which directly couples to a magnetic field [2]. For example, one can use a rotating magnetic field, which is applied to one end of the sample and is strong enough to orient the magnetization parallel to it. Because of the stiffness of the spin system, the spin rotation at one end is transmitted to the other end of the sample, which is not subject to the direct effect of the rotating magnetic field. Transmission of the torque through the sample presents a spin current.

The incoherent current injection method to drive the sliding has already been proposed by us in Ref.[3]. In our recent paper [4] we proposed that chiral helimagnets are promising candidates to realize the coherent method. In particularly, we demonstrated that the chiral soliton lattice in a chiral helimagnet exhibits a sliding motion when a time-dependent magnetic field is applied parallel to the helical axis, in addition to a static field perpendicular to the helical axis. As it has been pointed out in Ref. [5], once the sliding is triggered, the soliton lattice maintains its persistent motion assisted by a generation of inertial mass. Another observable consequence of the coherent motion is an appearance of the spin motive force (SMF) [6], when the time dependence of the longitudinal magnetic field manifests itself in the temporal regime of the SMF. As a remarkable feature, we note that the chiral soliton lattice is a macroscopically ordered object, which contains macroscopic amounts of magnetic solitons (kinks). Due to this very large number of the solitons, the SMF is expected to be strongly amplified as compared with the SMF caused by a single magnetic domain wall in a ferromagnet. Numerical estimations show that the SMF reaches the order of millivolts that makes chiral magnetic crystals to be extremely promising for spintronic applications.

References

[1] I. Žutić , J. Fabian, and S. Das. Sarma, *Rev. Mod. Phys.* **76**, 323 (2004)
[2] E. B. Sonin, *Adv. Phys.* **59**, 181 (2010)
[3] J. I. Kishine, I. V. Proskurin, and A. S. Ovchinnikov, *Phys. Rev. B* **82**, 064407 (2010)
[4] J. Kishine, I.G. Bostrem, A.S. Ovchinnikov, Vl.E. Sinitsyn, *Phys. Rev. B* **86**, 214426 (2012)
[5] I. G. Bostrem, J. I. Kishine, and A. S. Ovchinnikov, *Phys. Rev. B* **77**, 132405 (2008); *ibid.* **78**, 064425 (2008)
[6] S. E. Barnes and S. Maekawa, *Phys. Rev. Lett.* **98**, 246601 (2007)

Spin polarization in strained epitaxial $Fe_{1-x}Co_xSi$ thin films

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FeSi is a non-magnetic narrow bandgap semiconductor, which belongs to T^4 $P2_13$ space group and crystallises in B20 structure. The competition between short range ferromagnetic interaction and Dzyaloshinskii-Moriya interaction (DMI) in broken inversion symmetry B20 structure gives rise to helimagnetic ordering in the crystal structure. Upon doping FeSi with Co, Co substitutes onto a Fe site and transforms FeSi into a magnetic n-type semiconductor [1], before becoming metallic at high doping densities. Almost all the previous work so far has studied bulk material. We have studied the growth and Co-doping dependence of the structural, transport and magnetic properties of ε-$Fe_{1-x}Co_xSi$ epilayers grown by molecular beam epitaxy on silicon (111) substrates.

LEED, AFM, XRD (Fig.1) and HRTEM studies have confirmed the growth of phase pure, defect free ε-$Fe_{1-x}Co_xSi$ epitaxial films with a surface roughness of 1-2 nm. Unlike the B20 (cubic) phase which is stable in bulk, these epilayers are tensile strained in-plane and are compressively strained out of plane to become rhombohedral. Strain increases the net volume of the crystal structure and induces anisotropy and further influences the magnetic ordering and transport properties of ε-$Fe_{1-x}Co_xSi$ epilayers.

Measurement of the ordinary Hall effect confirms the successful substitution of Fe by Co and the addition of one conduction electron per Co dopant. We also observe huge Anomalous Hall effect with R_S (anomalous Hall coefficient) = 0.56 cm^3 C^{-1} at 5 K which is more than that observed in the bulk. The temperature dependence of the resistivity falls as the Co concentration is increased, being semiconducting-like for low x and metallic for $x > 0.4$ (Fig. 2). The ε-$Fe_{1-x}Co_xSi$ films exhibit positive linear magnetoresistance (10%) below T_C. Whilst the MR is fully reversible, SQUID loops show magnetic hysteresis similar to polycrystalline thin films [2] but unlike bulk material. The Curie temperatures are higher than in bulk, up to 77 K for $x = 0.4$ (Fig.3 (b)), as observed using SQUID and VSM measurements (Fig.3 (a)). The saturation magnetic moment of the films varies as a function of Co doping and further calculation indicates contribution of approx. 1 μB / Co atom for $x \leq 0.25$ (Fig.3 (c)). In combination with the carrier density, this signifies a very highly spin-polarised electron gas in the low x, semiconducting regime.

This work was supported by the EPSRC and the FP7 ITN Q-NET.

References

[1] N.Manyala *et al*., *Nature* **404**, 581 (2000)
[2] N. A. Porter *et al*., *Phy.Rev.B*, **86**, 064423 (2012)
[3] N.Manyala *et al*., *Appl.Phys. Lett.*, **94**, 232503 (2009)
[4] Y. Onose *et al.*, *Phys. Rev. B*, **72**, 224431 (2005)
[5] S. V. Grigoriev *et al. Phys. Rev. B*, **76**, 224424 (2007)

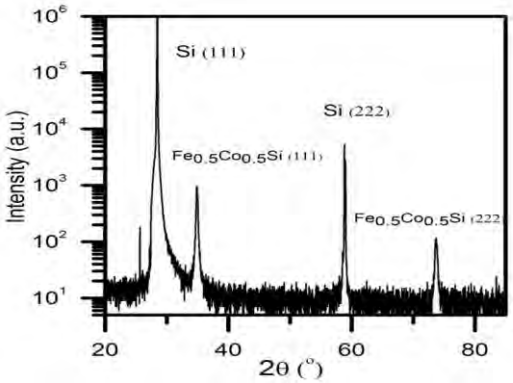

Fig. 1 *High angle XRD scan of a ε-$Fe_{1-x}Co_xSi$ film showing characteristic B20 peaks.*

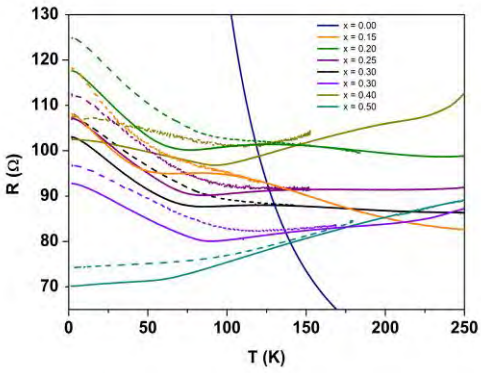

Fig. 2 *Temp. Vs resistance for ε-$Fe_{1-x}Co_xSi$ films with varying Co doping.*

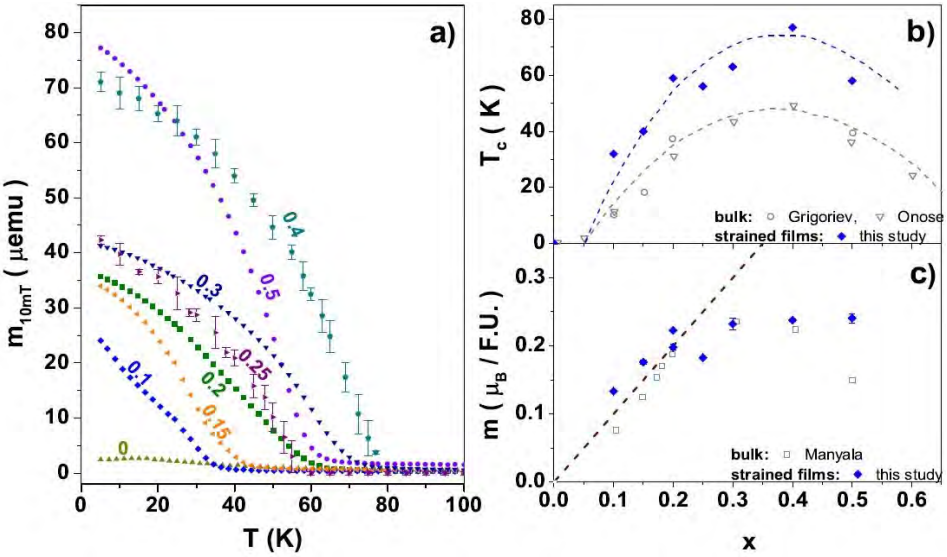

Fig. 3 *a) Magnetization of ε-$Fe_{1-x}Co_xSi$ films at 10 mT field. b) Enhanced T_c of ε-$Fe_{1-x}Co_xSi$ films relative to bulk samples. c) Variation of Bohr magneton per formula unit (F.U.) as a function of varying Co content.*

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