Konstantinov Petersburg Nuclear Physics Institute
of National Research Centre "Kurchatov Institute"

International Workshop

"Dzyaloshinskii-Moriya Interaction and Exotic Spin Structures"

Abstracts and program

23-26 May 2017
Peterhof, Russia

http://oiks.pnpi.spb.ru/events/DMI-2017

International Workshop

“Dzyaloshinskii-Moriya Interaction and Exotic Spin Structures ”

TOPICS

- Crystal handedness and spin chirality.
- Critical spin fluctuations at the phase transition in helimagnets.
- Monoaxial chiral helimagnets
- Chiral couplings and phase transitions in helimagnets.
- Phase transitions in helimagnets.
- Spin excitations in helimagnets with DM interaction
- Exotic spin structures (skyrmions) – I
- Exotic spin structures (skyrmions) – II
- Theory of DMI effect on the magnetic structure
- Hall effect in chiral magnetic structures
- Thin films and surface effects in cubic ferromagnets without center of symmetry.
- Antiferromagnets and multiferroics
- Neutron scattering for non-collinear magnetism

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- Co-Chairman: **Jun-ichiro Kishine** (*The Open University of Japan, Japan*)
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Programme

Tuesday. 23 May 2017

8.00 – 13.30	**Check in at the hotel, Registration, Lunch**	
13.50 – 14.00	**Opening ceremony**	
Session 1. Crystal handedness and spin chirality. Chairperson **Catherine Pappas**		
14.00 – 14.30	**Gen Tatara** Dr., RIKEN, Japan	«Doppler shift picture of Dzyaloshinskii-Moriya interaction»
14.30 – 15.00	**Rostislav Mikhaylovskiy** Mr, Radboud University, The Netherlands	«Femtosecond Opto-magnetism in Materials with the Dzyaloshinskii-Moriya Interaction»
15.00 – 15.30	**Ohta Hitoshi** Prof., Kobe University, Molecular Photoscience Research Center, Japan	«Determination of DMI in Kagome Lattice Antiferromagnet Cr-Jarosite by High-Frequency ESR»
15.30 -16.00	**Coffee break**	
Session 2. MnGe-based helimagnets. Chairman **Vladimir Dmitrienko**		
16.00 – 16.30	**Isabelle Mirebeau** Prof., LLB, Saclay, France	«Two-step pressure induced collapse of magnetic order and fluctuating chiral phase in MnGe chiral magnet»
16.30 – 16.50	**Gleb Valkovskiy** Dr., Saint-Petersburg State University, St-Petersburg, Russia	«Small structural variation and various physical properties of the B20 type compounds»
16.50 – 17.20	**Vladimir Sidorov,** Dr.,Vereshchagin Institute for High Pressure Physics, RAS, Moscow, Troitsk, Russia	«Effect of high pressure on the properties of cubic noncentrosymmetric compounds of $Mn_{1-x}Rh_xGe$»
17.20 – 17.40	**Nicolas Martin** Dr., LLB, Saclay, France	«Long-period smectic-like magnetic structures in $Mn_{1-x}(Co,Rh)_xGe$ alloys»
17.40 – 18.00	**Evgeny Altynbayev** Mr., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	«Fragile equilibrium in Fe and Co-doped MnGe compounds»
18.00 – 18.20	**P. Kizhe**	«Spin wave stiffness in $Mn_{1-x}Fe_xGe$

	Dr., Grad-Kitezh University,Grad-Kitezh, Russia	helimagnets studied by SANS»
19.00	**Welcome party**	
Wednesday. 24 May 2017		
Session 3. Monoaxial chiral helimagnets . Chairman **Javier Campo**		
9.00 – 9.30	**Jun-ichiro Kishine** Prof., The Open University of Japan, Japan	«Mono-axial chirality in magnetism and optics»
9.30 – 10.00	**Yoshihiko Togawa,** Dr.,Osaka Prefecture University, Japan	«Structure and Functionality of Chiral Monoaxial Magnetic Crystals»
10.00– 10.30	**Masayuki Hagiwara** Prof., Osaka University, Osaka, Japan	«Spiked structures on esr signals of the chiral helimagnet $CrNb_3S_6$»
10.30 – 10.50	**Yusuke Kato,** Prof., The University of Tokyo, Tokyo, Japan	«Spin structures in precursor region of uniaxial chiral magnets»
10.50 – 11.20	**Shigeo Ohara,** Prof., Nagoya Institute of Technology, Nagoya, Japan	Magnetic phase diagram of uniaxial chiral helical magnet $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$
11.20 – 11.30	**Coffee break**	
Session 4. Chiral couplings and phase transitions in helimagnets. Chairman **Jun–ichiro Kishine**		
11.30 – 12.00	**Alexander S. Ovchinnikov** Prof., Ural Federal University Ekaterinburg, Russia	« Functional RG analysis of Pokrovsky-Talapov model »
12.00 – 12.20	**Alexander M. Belemuk** Institute for High Pressure Physics of RAS, Moscow, Russia	«Phase transitions in chiral magnets from Monte Carlo simulation»
12.20 – 12.40	**Oleg Utesov** Dr., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	«Cascades of phase transitions in spiral magnets caused by dipolar forces»
12.40 – 13.00	**Javier Campo** Prof., Instituto de Ciencia de	«Nucleation, Instability and discountinuos phase transitions in the

	Materiales de Aragón – Universidad de Zaragoza, Zaragoza, Spain	monoaxial helimagnet with oblique fields»
13.00 – 14.00	**Lunch**	
Session 5. Phase transitions in helimagnets. Chairman **Yoshihiko Togawa**		
14.00– 14.30	**Catherine Pappas** Prof., TUDelft, Delft, Netherlands	«Phase transition of MnSi under magnetic field: A SANS and Neutron Spin Echo Study»
14.30 – 14.50	**Alla Petrova** Dr., Institute for High Pressure Physics of RAS, Moscow, Russia	«On phase diagram of the itinerant helical magnet MnSi at strong magnetic fields»
14.50 – 15.10	**Fengjiao Qian** Ms., TUDelft, Delft, Netherlands	«Dissipation phenomena and magnetic phase diagram of Cu_2OSeO_3»
15.10 – 15.30	**Misako Shinozaki** Dr., The University of Tokyo, Tokyo, Japan	«Metastability and Hysteresis in Chiral Helimagnet»
15.30 – 16.00	**Coffee break**	
Session 6. Spin excitations in helimagnets with DM interaction Chairman **Arsen Gukasov**		
16.00 – 16.30	**Tobias Weber** Dr., Technische Universität München, Munich, Germany	«From helimagnons towards non-reciprocal spin-waves in MnSi »
16.30 – 17.00	**Sergey Grigoriev** Dr., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	«Spin wave stiffness in $Mn_{1-x}Fe_xSi$ helimagnets studied by SANS»
17.00 – 17.20	**Francisco Jose Trindade Goncalves** Dr., Osaka Prefecture University, Osaka, Japan	«Spin wave propagation in a chiral monoaxial crystal $CrNb_3S_6$»
17.20 – 17.40	**Sergey Maleyev,** Prof., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	« DM helices and magnetic field »
17.40 – 18.00	**Igor Proskurin** Dr., The Open University of	«Spin-wave chirality and its manifestation in antiferromagnets»

	Japan, Chiba,Japan	
18.00	**Evening in St-Petersburg**	

Thursday 25 May 2017

Session 7. Exotic spin structures (skyrmions) - I
Chairman **Ted Monchesky**

9.00 – 9.30	**Sergey Demishev** Prof., Prokhorov General Physics Institute of RAS, Moscow, Russia	«Different Skyrmion Lattice States in the A-Phase of MnSi Revealed by Magnetoresistance Probing»
9.30 – 9.50	**Lars Bannenberg** Mr., TUDelft, Delft, Netherlands	«Unraveling the coupling between skyrmion and crystallographic lattices»
9.50 – 10.10	**Victor Ukleev** Dr., CEMS, RIKEN, Japan	«Topological spin textures probed by coherent resonant soft X-ray scattering»
10.10 – 10.40	**Victor Laliena,** Prof. Instituto de Ciencia de Materiales de Aragón – Universidad de Zaragoza, Zaragoza, Spain	«Stability of Skyrmionic textures in cubic helimagnets and the role of fluctuations.»
10.40 – 11.00	**Nadya Chubova** Dr., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	«Conical lattice versus skyrmion lattice in MnSi: competition of two structures above T_C.»
11.00 – 11.20	**Takashi Kurumaji** Dr., RIKEN Center for Emergent Matter Science, Japan	«Neel-type Skyrmion lattice formation in a new class of polar magnet»
11.20 – 12.20	**Coffee break, Poster session**	

Session 8. Theory of DMI effect on the magnetic structure
Chairman **Dmitry N. Aristov**

12.20 – 12.40	**Maria Jose Martinez-Perez,** Dr., University of Zaragoza, Spain	«Individual magnetic vortices invesgtigated by nanosquid magnetometry»
12.40 – 13.00	**Laura Köhler** Ms., IFW Dresden, Dresden, Germany	«Topological domain walls in helimagnets»

13.00 – 14.00	**Lunch**	
Session 9. Exotic spin structures (skyrmions) - II Chairman **Alexander S. Ovchinnikov**		
14.00 – 14.30	**Dmitry Aristov,** Dr., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	«Stability of a skyrmion and interaction of magnons»
14.30 – 15.00	**Victor Mironov** Dr., Institute for physics of microstructures RAS, Russia	«Skyrmion spin-wave resonances in ferromagnetic film with spatially modulated perpendicular anisotropy»
15.00 – 15.20	**Andrey Tsypilnikov,** Mr., NRC "Kurchatov Institute" - PNPI, Gatchina, Russia	«Magnon spectrum in magnetic materials with skyrmion superlattice»
15.00 – 15.20	**Coffee break**	

Session 10. Hall effect in chiral magnetic structures
Chairman **Sergey V. Demishev**

15.40 – 16.10	**Vladimir V. Glushkov,** Prof., A.M. Prokhorov General Physics Institute Moscow, Russia	«Fermi Surface Evolution and Quantum Criticality in $Mn_{1-x}Fe_xSi$»
16.10 – 16.30	**Inna Lobanova,** Dr., Prokhorov General Physics Institute of RAS, Moscow, Russia	«Effect of magnetic field on the intermediate phase in $Mn_{1-x}Fe_xSi$: spin-liquid vs. fluctuations scenario»

Session 11. Thin films and surface effects in cubic ferromagnets without center of symmetry
Chairman **Sergey V. Demishev**

16.30 – 17.00	**Ted Monchesky,** Prof., Dalhousie University, Halifax, Canada	«Chiral magnetic states in MnSi thin films»
17.00 – 17.20	**Dirk Menzel,** Dr., TU Braunschweig, Institute for Condensed Matter Physics, Braunschweig, Germany	«Electronic Transport in MnSi Thin Films and Nanostructures»
17.20 – 17.40	**Vyacheslav Gritzaenko** IRC "Smart Materials", Southern Federal University,	«Time-dependent entanglement within a framework of Dzyaloshinskii-Moriya interaction effect»

	Rostov-on-Don, Russia	
17.40	**Evening in St-Petersburg (free time)**	

Friday 26 May 2017

Session 12. Antiferromagnets and multiferroics
Chairperson **Isabelle Mirebeau**

9.00 – 9.30	**Vladimir Dmitrienko** Prof. Dr., A.V.Shubnikov Institute of Crystallography RAS, Moscow, Russia	«Spin-orbit effects in non-collinear magnetism»
9.30 – 10.00	**Kazuhisa Kakurai** Prof., Japan Atomic Energy Agency, Tokai, JAPAN	«Magnetic structure and excitations in multiferroic hexaferrites »
10.00 – 10.20	**Igor Zobkalo** Dr., NRC "Kurchatov Institute" - PNPI Gatchina, Russia	«Chirality evolution in RMn2O5 multiferroics»
10.20 – 10.40	**Andrey Fraerman,** Prof., Institute for physics of microstructures RAS, Nizhny Novgorod, Russia	«Second harmonic generation in non-collinear magnetic system due to spin current: theory and experiment »
10.40 – 11.00	**Vadim Dyadkin** Dr. SNBL, ESRF Grenoble, France	«Probing chirality with high energy synchrotron light»
11.00 – 11.30	**Coffee break**	

Session 13. Neutron scattering for non-collinear magnetism
Chairman **Kazuhisa Kakurai**

11.30 – 12.00	**Arsen Gukasov** Prof., LLB, Saclay, France	«Bilayered crystal of magnetic monopoles and multiferroicity in spin ice »
12.00 – 12.20	**Dmitriy Tatarskiy** Mr., Institute for physics of microstructures RAS, Russia	«Nonreciprocal neutron diffraction on helical magnets»
12.20 – 12.40	**Konstantin Metlov** Dr. Donetsk Institute for Physics and Technology, Donetsk	«Micromagnetic theory of a third-order effect in magnetic small-angle neutron scattering by a spatially inhomogeneous medium»
12.40 – 13.00	**Alexander Kurbakov,**	«Magnetism of layered triangular

	Dr., NRC «Kurchatov Institute» - PNPI, Gatchina, Russia	antimonates and tellurates with and without existence of structural and magnetic chiralities coupling»
13.00 – 14.30	**Lunch**	
15.00 – 19.00	**Excursion through town Peterhof**	
19.00 – 22.00	**Closure of conference and Conference dinner**	

Poster session

(11:00-12:00 Thursday 25 May 2017)

Tatiana Ischenko, Dr., A.M. Prokhorov General Physics Institute Moscow, Russia	«Mn_{1-x}FexSi as a liquid crystal»
Alexey Bykov, Dr., NRC «Kurchatov Institute» - PNPI, Gatchina, Russia	«Quasi two-dimensional character of the magnetic transition in YMn_6Sn_6»
Denis Salamatin, Mr., Institute of High Pressure physics, Moscow, Russia	«Incommensurate antiferromagnetism induced by a charge density wave in the cubic phases of $REGe_{2.85}$ (RE = Tb, Dy)»
Alexander Samarin, Mr., Prokhorov General Physics Institute of RAS, Moscow, Russia	«Magnetic Field Induced Griffiths Phase in $Mn_{1-x}Fe_xSi$ Solid Solutions»
Yusuke Araki, Mr., University of Tokyo, Tokyo, Japan	«Magnetic and magnetoelectric properties in a chiral polar magnet Ni_2InSbO_6»
Victor Timofeev, Mr., NRC «Kurchatov Institute» - PNPI, Gatchina, Russia	« Stereographic projection approach to skyrmionic spin structures»
Kirill Pschenichnyi, Mr., Saint Petersburg State University, St-Petersburg, Russia	«Neutron scattering cross sectionon the spin-waves in full polarized state in helimagnets »
Igor Golosovskiy, Dr., NRC «Kurchatov Institute» - PNPI, Gatchina, Russia	«Incommensurate magnetic order in CoO nanoparticles revealed by neutron diffraction»
Mikhail Prosnikov Mr., Ioffe Institute, Petersburg, Russia	«Raman scattering study of the magnetic dynamics in $PbFeBO_4$ induced by the Dzyaloshinskii-Moriya interaction»
Mariia Kuchugura, Ms., NRC «Kurchatov Institute» - PNPI, Gatchina, Russia	«The diffraction study of new low-dimensional spin frustrated chiral $MnSnTeO_6$»
Maria.V. Magnitskaya, Dr., Institute of High Pressure physics, Moscow, Russia	«Electric field gradients in B20 compounds: Experiment and ab initio calculation»
Tsuyoshi Omi, Mr., The University of Tokyo, Tokyo, Japan	«Observation of a nonreciprocal signal in ferromagnetic resonance in multiferroic $GaFeO_3$»
Kunio Tokushuku Mr. The University of Tokyo, Tokyo, Japan	«Dynamics of chiral soliton lattice under an electric field and its magnetic dependence»

Session 1. Crystal handedness and spin chirality.

Chairman: Dr. Catherine Pappas

Doppler shift picture of the Dzyaloshinskii-Moriya interaction and light propagation in systems with broken inversion symmetry

Toru Kikuchi, Junya Shibata, Hideo Kawaguchi, Takashi Koretsune, Ryotaro Arita, Hiroshi Kohno, Akihito Takeuchi, Gen Tatara

RIKEN Center for Emergent Matter Science (CEMS)

We present a physical picture for the emergence of the Dzyaloshinskii-Moriya (DM) in-teraction based on the idea of the Doppler shift by an intrinsic spin current induced by spin-orbit interaction under broken inversion symmetry such as the case with Rashba inter-action [1]. The picture is con rmed by a rigorous eﬀective Hamiltonian theory, which reveals that the DM coefficient is given by the magnitude of the intrinsic spin current. The expres-sion is directly applicable to rst principles calculations and clari es the relation between the interaction and the electronic band structures. Quantitative agreement with experimental results is obtained for the skyrmion compounds $Mn_{1\ x}Fe_xGe$ and $Fe_{1\ x}Co_xGe$. The Doppler shift occurs for incoming electromagnetic wave, too, when the Rashba interaction and mag-netization are present, resulting in directional dichroism [2, 3]. The eﬀective Hamiltonian for the electromagnetic eld is shown to the vector type, u (E B), where u corresponds to the intrinsic velocity due to the troidal moment [3].

References

[1] T. Kikuchi, T. Koretsune, R. Arita, G. Tatara, *Phys. Rev. Lett.*, **116**, 247201 (2016).
[2] J. Shibata, A. Takeuchi, H. Kohno and G. Tatara, *J. Phys. Soc. Japan*, **85**, 033701 (2016).
[3] H. Kawaguchi and G. Tatara, *Phys. Rev. B* **94**, 235148 (2016).

Femtosecond Opto-magnetism in Materials with the Dzyaloshinskii-Moriya Interaction

A. V. Kimel
Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands
Moscow Technological University (MIREA), Moscow, Russian Federation

Ultrafast control of magnetic state of media with the help of femtosecond laser pulses is a counter-intuitive and rapidly developing research area with a potential to influence future information processing technologies. The action of electric field of light on electronic dipoles, being the largest perturbation in physics of light-matter interaction, conserves the spin of electron. Therefore mechanisms allowing an effective and ultrafast optical control of magnetism are a subject of intense debates. Materials with the Dzyaloshinskii-Moriya interaction become very popular model systems in the field of femtosecond opto-magnetism [1-6]. In my talk I will try to explain the reasons of such popularity by reviewing experimental studies of optical control of spins in iron-oxides with the Dzyaloshinskii-Moriya interaction.

References:

[1] A. V. Kimel et al, *Nature* 435, **655** (2005).
[2] D.Afanasiev et al, *Phys.Rev Lett*. **112** 147403 (2014).
[3] R. Mikhaylovskiy et al, *Nature Communications* **6**, 8190 (2015).
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[5] S. Baierl et al, *Nature Photonics* **10**, 715 (2016).
[6] T. F. Nova et al, *Nature Physics* doi:10.1038/nphys3925 (2016).

Determination of DMI in Kagome Lattice Antiferromagnet Cr-Jarosite by High-Frequency ESR

H. Ohta[1], S. Okubo[1], R. Nakata[2], S. Ikeda[2], N. Takahashi[2], T. Sakurai[3], W-M Zhang[1], T. Shimokawa[4], T. Sakai[5], K. Okuta[6], S. Hara[3], and H. Sato[6]
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Recently geometrical frustration has attracted much attention because it induces novel effects as a result of enhanced fluctuations. Especially among two-dimensional frustrated systems, the kagome lattice antiferromagnet is the most interesting system because it is theoretically considered to have the highest frustration, that is, the highest degree of the degenerate ground state. On the other hand, as high quality model substances are essential for the experimental studies, investigations for the model substance of kagome lattice antifferromagnet have been done intensively. Moreover, as the existence of Dzyaloshinsky- Moriya interaction (DMI) is unavoidable due to the lattice symmetry of kagome lattice, the determination of DMI for each model substance is also the important issue because it affects the ground state of system.

Cr-jarosite [$KCr_3(OH)_6(SO_4)_2$] is considered to be one of ideal model substances of S=3/2 kagome lattice antiferromagnet, and has been studied intensively. Recently Okuta *et al.* [1] succeeded in synthesizing high quality single crystals of Cr-jarosite that had no defects in the Cr ion sites. This is rather important because previously reported magnetic properties of Cr-jarosite have been rather controversial, reflecting the difficulty in preparing good powder samples. Moreover, the synthesis of single crystal is also important to study the magnetic anisotropy, and Okuta *et al.* revealed the spontaneous magnetization of 0.05 μ_B/Cr along the c -axis (perpendicular to the kagome plane) below T_N=4.5 K.

As high-frequency high-field ESR is a powerful means of studying kagome lattice model substances and determining the magnetic anisotropies, we have performed polycrystalline and single crystals of Cr-jarosite from Okuta *et al.* in the temperature region from 1.9 to 265K using a pulsed magnetic field up to 16 T. The frequency region is from 80 to 481 GHz. First the g-values perpendicular to the kagome plane (c-axis) and in the plane were determined to be $g_c = 1.9704 \pm 0.0002$ and $g_{per} = 1.9720 \pm 0.0003$, respectively, by high- frequency ESR at 265 K. Then antiferromagnetic resonances (AFMRs) with an antiferromagnetic gap of 120 GHz were observed at 1.9 K. DMI of Cr-jarosite is determined from the analyses of AFMR modes by the molecular field theory. The ground state of Cr- jarosite will be discussed in connection with the Monte Carlo simulation results with classical Heisenberg spins on the kagome lattice by Elhajal *et al*. [3].

References:

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Session 2. MnGe-based helimagnets.

Chairman: Dr. Vladimir Dmitrienko

Two step pressure induced collapse of magnetic order and fluctuating chiral phase in MnGe Chiral magnet

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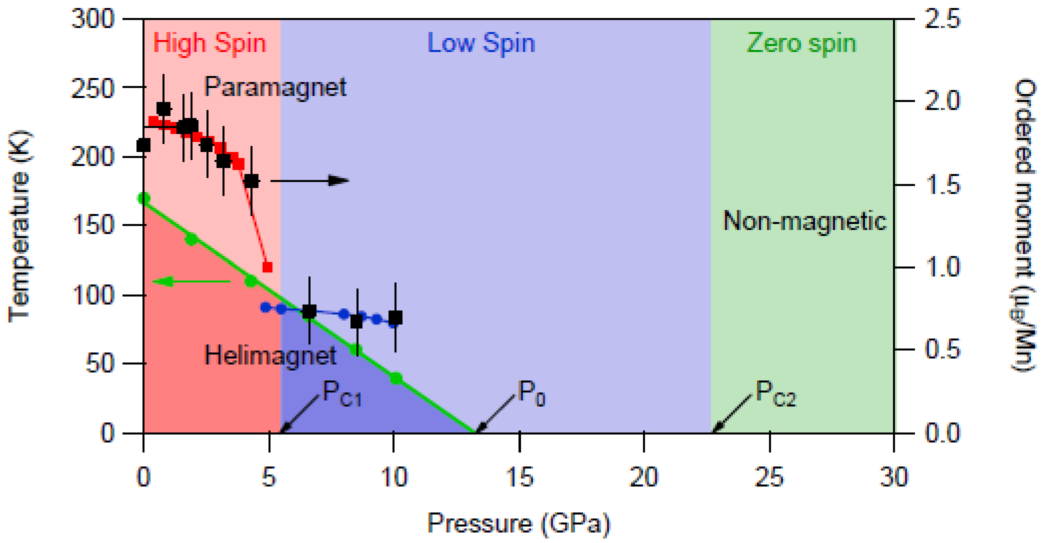
Itinerant magnets generally exhibit pressure-induced transitions towards nonmagnetic states. By combining resistivity, ac-susceptibility and neutron diffraction up to very high pressure, we previously observed a two-step pressure induced collapse of MnGe chiral magnet in its helically ordered ground state. The helical order transforms around 6 GPa from a high-spin to a low-spin state, recalling the weak ferromagnetism of MnSi at ambient pressure. Helical order collapses only above 10 GPa. The spin-state transition is supported by *ab initio* calculations [1].

Using synchrotron-based x-ray diffraction and emission spectroscopy [2], we have been able to probe this collapse at a local scale in the *paramagnetic* state. As in the ground state, the collapse of the spin moment takes place in two steps. The evolution of the lattice constant and spin moment in the chiral magnet MnGe was investigated at 300 K under pressures up to 38 GPa. A first-order transition with a huge hysteresis around 7 GPa transforms the system from the high-spin state at ambient pressure to a low-spin state, yielding irreversibilities of the lattice constant. The coexistence of spin states and observation of history-depending irreversibility is explained as the effect of long-range elastic strains mediated by magneto-volume coupling, within the thermodynamic picture proposed for a two- phase system [3]. Only in a second transition, at about 23 GPa, does the spin moment collapse, as shown by X ray emission spectroscopy. Combining the whole set of data provides a phase diagram for MnGe under pressure (Figure). The results also call for an Invar-like behavior of MnGe.

Helical order and magnetic fluctuations previously studied by Mössbauer spectroscopy and small angle neutron scattering [4] have been re- investigated using muon spin resonance (μSR) [5]. Magnetic fluctuations coexist with ordered helices in a broad temperature range of about ± 70 K around the Néel temperature (T_N = 170K). At low temperature (5 K), the muon polarization shows double-period oscillations at short-time scales. Their analysis, akin to that recently developed for MnSi [6] provides an estimate of the field distribution induced by the Mn helical order at the muon site. The refined muon position agrees nicely with *ab initio* calculations. With increasing temperature, the inhomogeneous fluctuating chiral phase sets in. It can be characterized either by two well-separated frequency ranges coexisting in the sample, or by a broad distribution of time scale evolving with temperature. Rapid and slow fluctuations, tentatively associated with short-range and long-range ordered helices respectively, coexist in a large temperature range up to T_N.

We discuss the results with respect to MnSi, taking the short helical period, metastable quenched state, and peculiar band structure of MnGe into account.



MnGe pressure temperature phase diagram deduced from neutron diffraction [1], and synchrotron-based X-ray techniques [2].

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Small structural variation and various physical properties of the B20 type compounds

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All the compounds MnGe, MnSi, FeGe, FeSi, CoGe, CoSi generally crystallize in B20 type structure. Still, their physical properties (magnetic, electronic, thermodynamic) are essentially different and depend sensitively on the unit cell volume (pressure, temperature, concentration of solid solution) [1-2]. For instance, MnGe and FeSi possess an anomalous thermal expansion and temperature dependence of the magnetic susceptibility [3-5]. Although, in practice there is a small deviation from the so-called ideal B20 structure, where all seven nearest-neighbour metal-ligand bonds have the same length [6].

Our work attempts to bring into correlation the deviation from the ideal B20 structure for the above mentioned compounds and the variation of their physical properties. In this respect effects of pressure and temperature are also considered in terms of the local bonding picture. In particular, the structure of MnGe becomes closer to the ideal B20 under pressure along with decreasing of the magnetic moment [7]. Upon heating the deviation for the ideal B20 increases for MnGe in contrast to FeSi, the reason for this behaviour is not entirely clear. Probably, there is a certain electron-phonon coupling, i.e. a correlation between low-symmetry ligand arrangement and the 3d electronic structure of the transition metal.

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Effect of high pressure on the properties of cubic noncentrosymmetric compounds MnGe-RhGe.

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The compounds with a cubic noncentrosymmetric B20 structure like MnSi and FeGe attracted much attention due to their nontrivial properties: long period chiral magnetism, skyrmion lattices, topological Hall-effect, pressure induced quantum criticality etc. Recently properties of pressure-synthesized B20 phase of RhGe were studied [1]. It was found that the net weak ferromagnetic polarization below T_m ~140 K coexists with superconductivity below T_c ~4 K. Ab-initio simulations suggest that the observed weak magnetization of RhGe emerges from the pronounced toroidal-like spin polarization with magnetic quadrupole and toroidal moments located at Rh and Ge sites. Andreev reflection spectroscopy on RhGe below T_c shows that the superconducting order parameter may be a mixture of spin-singlet and spin-triplet components that was theoretically predicted for noncentrosymmetric magnets. Monogermanides of magnetic 3d-manganese and nonmagnetic 4d rhodium form a continuous series of solid solutions with B20 structure during synthesis under high pressure. Substitution of Mn for Rh in the series should produce a change of a chiral magnetism of MnGe to a nontrivial weak magnetism of RhGe. We have studied the magnetic properties of $Mn_{1-x}Rh_xGe$ compounds at ambient and high pressures to explore how this transformation goes on. On the Mn-side of a series (up to x = 0.3) the broad peak in the temperature dependence of magnetic susceptibility signals the onset of a chiral magnetic order. Magnetization measurements reveal the transition from helical to field-induced ferromagnetic state at fields above 5 T as it was observed for MnGe [2,3]. At high pressure the peak of magnetic susceptibility shifts to lower temperatures indicating that pressure suppress the helical spin order, similar to MnGe [4]. Change of the magnetic state of $Mn_{1-x}Rh_xGe$ takes place between x = 0.3 and x = 0.5. For samples of Rh-rich side of a series the magnetic susceptibility increases in a step-like manner at the magnetic transition. The magnetic moment of these samples exhibits saturation at relatively low field ~0.5 T and systematically decreases as Rh concentration x increases. The magnetic transition temperature T_m gradually decreases from T_m = 160 K for x = 0.5 to T_m ~140 K for x = 0.975 that is very close to T_m of RhGe [1]. So the system exhibits very unusual property: small changes of T_m (that is proportional to the strength of magnetic exchange) in a wide range of magnetic moment. Pressure dependences of T_m were studied for a few samples in the range $0.5 < x < 0.975$. For all these samples T_m increases with pressure at a rate 8.4 K/GPa in contrast to Mn-rich side of a series. Thus our pressure and magnetic field measurements show that the magnetic state of $Mn_{1-x}Rh_xGe$ compounds for $x > 0.5$ is different from the chiral magnetism of MnGe and is probably related with the unusual magnetism of RhGe calculated in [1]. Detailed experimental study of the magnetic structure of Rh-rich side of $Mn_{1-x}Rh_xGe$ system is in progress.

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Long-period smectic-like magnetic structures in $Mn_{1-x}(Co,Rh)_xGe$ alloys

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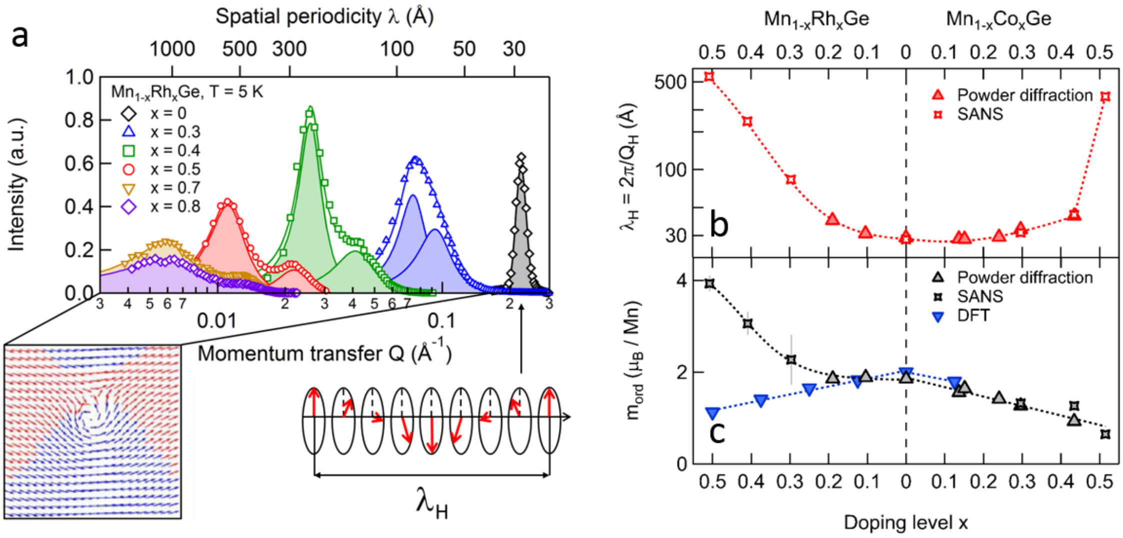
Despite tremendous experimental and theoretical activities in the field of magnetic skyrmions, effects of quenched disorder on the ground-state properties of their host chiral magnets remains widely unexplored up to now, especially in the case of newly synthetized cubic MnGe. It is however known from the physics of liquid crystals that novel properties may be expected when tuning the content of chiral species within a smectic or cholesteric parent compound.

Recently, it has been shown that a stepwise replacement of Mn by Fe in MnGe is an efficient way to control the chirality of the composite magnetic order **[1,2]**. However, both end constituents (MnGe and FeGe) are helimagnets in their pure form, so that the stabilization of long-range magnetic order over the whole $Mn_{1-x}Fe_xGe$-series is not surprising. Another way to address the role of disorder can be followed by substituting Mn by *non-magnetic ions*, possibly leading to loss of magnetism or partial ordering phenomena. In this frame, we present a study of $Mn_{1-x}(Co,Rh)_xGe$ alloys. At low temperature, pure MnGe hosts short wavelength spin helices (**Fig. a**) while CoGe and RhGe are examples of Pauli paramagnet **[3]** and unconventional superconductor **[4]**, respectively.

Upon substitution of Mn by Co and Rh, the helical wavelength is found to increase by a factor ≈ 30, while the ordered magnetic moment remains large (**Fig. b,c**). Above a doping level x ≈ 0.45 and 0.25 for Co and Rh substitution, respectively, neutron small-angle scattering reveals the formation of magnetic dislocations, whose core is composed of skyrmion-antiskyrmion pairs (inset of **Fig. a**). Such behavior is strongly reminiscent of the twist grain boundary phase observed at the interface between cholesteric and smectic liquid crystalline phases **[5]**. Moreover, by means of absolute scaling of neutron intensities, we observe a strong correlation between unit cell volume and ordered magnetic moment, in agreement with pressure-induced spin state transitions recently evidenced in MnGe by neutron and X-ray scattering **[6,7]**. Taken together, our results reveal new ways for tuning the microscopic properties of chiral magnets and prompting the stabilization of compact topological magnetic defects in their ground state.



(a) Effect of Rh-doping on MnGe as seen by small-angle neutron scattering.
(b) Doping dependence of the helical wavelength **(b)** and ordered magnetic moment **(c)** in $Mn_{1-x}(Co,Rh)_xGe$.

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Fragile equilibrium in Fe and Co-doped MnGe compounds

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We have grown $Mn_{1-x}Fe_xGe$ and $Mn_{1-x}Co_xGe$ compounds using high pressure method [1]. All samples have been tested with the x-ray diffraction and show *B*20 type structure without any other phases. The Small Angle Neutron Scattering (SANS) measurements were performed to study the transformations of the magnetic structure developing with temperature and/or concentration.

The magnetic (*T*-*x*) phase diagrams were built as a result of the experiments for $Mn_{1-x}Fe_xGe$ with $x < 0.7$ (Fig. 1 a) and for $Mn_{1-x}Co_xGe$ compounds with $x < 0.9$ (Fig. 1 b). In these pictures parameter α represents the fraction of the fluctuating spiral phase on the top of the stable phase. The stable spiral phase (LRO) with $\alpha < 0.1$ is the ground state of pure MnGe in the left-down corner of the diagrams. The line $\alpha = 1.0$ defines the point of the transition to the 100 % fluctuating spiral state. This temperature is denoted as T_N. The temperature T_h determines the upper border of the fluctuating spiral phase. The temperature T_{QF} defines the upper border of the quantum fluctuating state. The quantum nature of the SRO is proved by the temperature-independent correlation length of the helical structure at low- and intermediate-temperature ranges with remarkable decrease above certain temperature T_{QF}. The temperature T_{SRF} defines the lower border of the short-range ferromagnetic fluctuations. The temperature T_C corresponds to the transition of the magnetic structure to the paramagnetic state and was not observed for $Mn_{1-x}Fe_xGe$ compounds with $x < 0.45$ at temperature range $T < 300$ K.

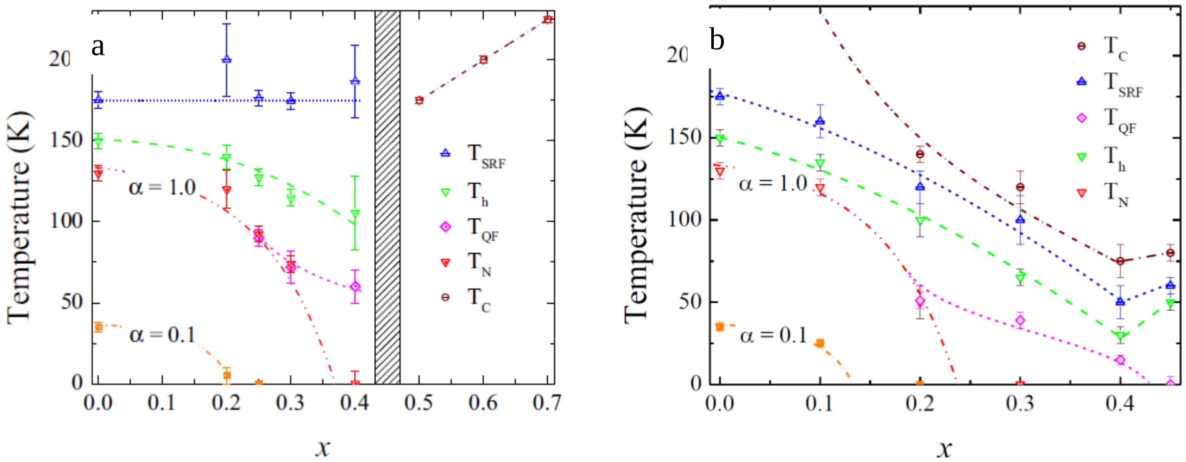

Figure 1: (T-x) phase diagram of the magnetic structure of $Mn_{1-x}Fe_xGe$ (a) and $Mn_{1-x}Co_xGe$ (b) compounds.

As one can see, the ordering temperature of the helical structure, T_N, decreases with the replacement of the Mn atoms with Fe or Co and drops to zero at $x_C = 0.35$ for $Mn_{1-x}Fe_xGe$ compounds and at $x_C = 0.25$ for $Mn_{1-x}Co_xGe$. Thus, we conclude that doping of MnGe with Fe or Co destabilizes its magnetic system. Moreover, the Fe or Co doping leads to the appearance of spiral fluctuations of quantum nature [2].

It is also found that $Mn_{1-x}Co_xGe$ orders magnetically at low temperatures in the whole concentration range of $x \leq 0.9$. The x-dependences of the helical wave vector value k at temperature T = 5 K and of the temperature of the magnetic phase transition, T_h, is presented in Fig. 2 for $Mn_{1-x}Co_xGe$ compounds. Three different states of the magnetic structure have been found: a short-period helical state at $x \leq 0.45$, a long-period helical state at $0.45 < x \leq 0.8$, and a ferromagnetic state at $x \sim 0.9$. Taking into account that the relatively large helical wave vector $k > 1$ nm^{-1} is characteristic for systems with mainly Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction, we suggest that the short-periodic helical structure at $x \leq 0.45$ is based on an effective RKKY interaction. Also the decay of k with increasing x is ascribed to a reduction of the interaction between second nearest neighbors and, therefore, to an increase of the influence of the Dzyaloshinskiy-Moriya interaction (DMI). The magnetic structure of $Mn_{1-x}Co_xGe$ compound with $x = 0.9$ is found to be ferromagnetic at low temperatures.

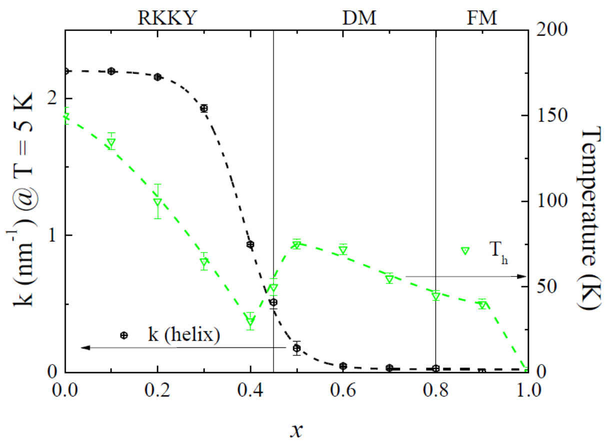

Figure 2: x-dependence of the helical wave vector value k at temperature T = 5 K and of the temperature of the magnetic phase transition, T_h, for $Mn_{1-x}Co_xGe$ compounds.

In summary, we suggest the x-dependent modification of the effective RKKY exchange interaction within the Heisenberg model of magnetism to explain the quantum critical regime in $Mn_{1-x}Fe_xGe$ and $Mn_{1-x}Co_xGe$. The evolution of the magnetic structure of $Mn_{1-x}Co_xGe$ with further x increase is an example of a continuous transition from a helical structure based on the effective RKKY to a helical structure based on DMI. The competition between the DMI ineraction and the cubic anysotropy finally brings the magnetic system to ferromagnetic state at low temperatures at $x > 0.8$.

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Spin waves in full-polarized state of dzyaloshinskii-Moriya helimagnets $Fe_{1-x}Mn_xGe$: small-angle neutron scattering study

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Magnetic susceptibility and neutron diffraction measurements have shown that the $Fe_{1-x}Mn_xGe$ compounds are magnetically ordered in the helical spin structure. The ordering temperature decreases smoothly with concentration x from the maximum (T_C = 278 K) for FeGe to T_C = 180 K for the compound with x = 0.5. The value of the wavevector k changes from 0.09 nm^{-1} for pure FeGe, through its minimum ($|k| \rightarrow 0$) at x_C = 0.25, to the value of 0.45 nm^{-1} for x = 0.5. 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 $x \rightarrow x_C$, which is explained by different signs of chirality for the compounds with $x > x_C$ and $x < x_C$ [1].

We report on the measurements of the spin-wave stiffness A and its temperature dependence close to T_C for the series of the compounds: FeGe and the solid solution compounds $Fe_{1-x}Mn_xGe$ with x = 0.0, 0.20. Recently we develop the technique to study the spin wave dynamics of the full-polarized state of the Dzyaloshinskii-Moriya helimagnets by small-angle neutron scattering [2, 3]. The neutron scattering image displays a circle with a certain radius, which is centered at the momentum transfer corresponding to $\mathbf{k}_s$, which is oriented along the applied magnetic field $\mathbf{H}$. The radius of this circle is directly related to the spin-wave stiffness of this system. We have experimentally proven for all compounds that the spin waves dispersion in this state has the anisotropic form: $E_q = A(\vec{q}-\vec{k}_s)^2 + (H - H_{C2})$, where A is the spin-wave stiffness and k_s is the helix wave vector in a helimagnetic phase and H_{C2} is the critical field of the transition from the conical to the fully-polarized state. The spin-wave stiffness A for FeGe-based helimagnets decreases with a temperature but has a finite value at T_C that classifies the order-disorder phase transition in FeGe-based compounds as being the first order one.

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Session 3. Monoaxial chiral helimagnets.

Chairman: Dr. Javier Campo

Mono-acial chirality in magnetism and optics

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The concept of chirality is ubiquitous in natural sciences. However, until only recently, research fields on chirality had been fragmented into separated branches of physics, chemistry and biology. Even inside physics, a term "chiral" has been used in different meanings in condensed matter and high-energy physics.

First of all, let us remind the Laurence Barron's definition of the true chirality, i.e., *true chirality is shown by systems existing in two distinct enantiomeric states that are interconverted by space inversion, but not by time reversal combined with any proper spatial rotation*. The space inversion is a matter of geometrical symmetry, while time reversal is a matter of dynamical motion. This unambiguous definition clearly indicates that the concept of chirality ties geometry and dynamics. Conversion of geometry into dynamics naturally leads to material functionalities.

The most widely known probe to detect chiral structure is light. Actually, the concept of chirality was first envisioned by Louis Pasteur through natural optical activity in chiral crystals. Propagating light carries helicity, which is truly chiral, and connects rotation and translation. This connection is nothing more than connection of geometry and dynamics. In this sense, any polarized beam such as ultrasound, neutron, muon can sense chiral structure. In particular, to use optical vortex which carry both intrinsic spin angular momentum and orbital angular momentum is of importance. Phonon and neutron vortices are also interesting from this viewpoint. Localized electromagnetic field, so-called "near field", can also sense chirality. Plasmon-assisted enhancement of circular dichroism is also promising to promote. One relevant issue is how to quantify the chirality. I will mention that so-called "Zilch" may play a crucial role.

Free electromagnetic field can be characterized by infinite number of conserving quantities. One of such quantities is the time-reversal even and spatial inversion odd pseudoscalar referred to as the optical chirality or Lipkin's Zilch. Applying symmetry analysis to the material form of Maxwell's equations, we investigate how the concept of optical chirality is generalized to different types of gyrotropic systems. Considering Born-Drude-Fedorov and chiral magnetoelectric constituent relations, we demonstrate that optical chirality remains well defined quantity in isotropic gyrotropic media. This description of optical chirality can be extended to the crystals belonging to cubic, hexagonal and tetragonal crystal classes when electromagnetic field propagates along the high symmetry direction, while for lower crystalline symmetries the definition of optical chirality becomes questionable.

I will discuss possible vortices in chiral helimagnets[1,2], called chiral soliton lattice, and also discuss relation between optical Zilch [3].

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Structure and Functionality of Chiral Monoaxial Magnetic Crystals

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A chiral magnetic crystal belonging to chiral space group is one of the most suitable material candidates that exhibit many kinds of emergent physical properties via nonlinear, robust, topological and tunable nature of chiral magnetic order. Various material functions provided by chiral magnetic materials and orders may lead to novel types of the spin electronics applications [1,2]. Furthermore, because of the universality of the concept of chirality underlying the functionality of chiral magnetic materials, chiral magnetism has attracted much attention in various research fields.

The formation of chiral magnetic order occurs as a consequence of the competition between Heisenberg symmetric and Dyzaloshinskii-Moriya (DM) antisymmetric exchange interactions in the presence of external magnetic field. The types of chiral magnetic order are categorized based on the symmetry of the chiral magnetic materials. The nature of the phase transition among the chiral magnetic order is still controversial and a matter of interest.

A chiral helimagnetic order (CHM) and chiral conical phase are widely recognized in the context of cubic chiral magnetic crystals and interfacial atomic layers. In those systems, the formation of a chiral magnetic vortex called magnetic Skyrmion has been extensively examined because of strong interest in the application to the memory device with a higher recording density [3]. The stabilization of magnetic Skyrmion is closely related to the stability of the other chiral magnetic phases.

Another essential thermodynamic phase in the chiral spin system is a nonlinear helicoidal superlattice called a chiral soliton lattice (CSL). The CSL was among the first chiral spin system envisioned by Dzyaloshinskii. Recently, the CSL has been directly visualized and analyzed in a hexagonal chiral magnetic crystal of $CrNb_3S_6$ by means of Lorentz microscopy and small-angle electron scattering [4]. Interestingly, the CSL exhibits the robust phase coherence in a macroscopic scale and is advantageous in extracting functionality of chiral magnetic crystal and order.

In this talk, I will present recent experimental results obtained in chiral magnetic materials of hexagonal $CrNb_3S_6$ crystal [4-8] via transport, RF resonance, and magnetization measurements and TEM magnetic imaging. These experimental findings provide us an important knowledge to progress the understanding of how chiral magnetic phases can survive in the competition among themselves and reveal the way to utilize various functions arising from the chiral topological orders unique to the chiral magnetic materials [1,2].

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Spiked structures on ESR signals of the chiral helimagnet $CrNb_3S_6$

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Some compounds with crystallographic chirality are named as chiral helimagnets (CHMs). The uniform Dzyaloshinskii-Moriya (DM) interaction and the exchange interaction cause a helical magnetic structure below a long-range ordering temperature.

In this presentation, we will report on the results of X- and K-band electron spin resonance (ESR) measurements of a single crystal sample of $CrNb_3S_6$, which is one of the CHMs, for the external H_{ext} and the microwave oscillating H_{mw} magnetic fields perpendicular to its helical axis (*c*-axis). The chiral soliton lattice (CSL) state is expected to appear in a finite H_{ext}. For X-band ESR, we utilized a field modulation technique with the frequency of 100 kHz. We observed some X-band ESR signals and spiked anomalous structures on the signals in the magnetic field range between H_{c1} and H_{c2} as shown in the inset of Fig. 1. By plotting H_{c1} and H_{c2} in magnetic field vs. temperature phase diagram, we have found three regions as shown in Fig. 1 that demonstrate different features of the ESR dynamic response in the CSL phase, and that the upper boundary was located close to that derived from the d^2M/dH^2 curve of this compound [1]. K-band ESR signals measured without the field modulation technique do not have such spiked anomalies. Consequently, the origin of the spiked anomalies on the X-band ESR signals may be ascribed to the formation and motion of an intermediate state induced by the modulating magnetic field used in the X-band ESR measurement.

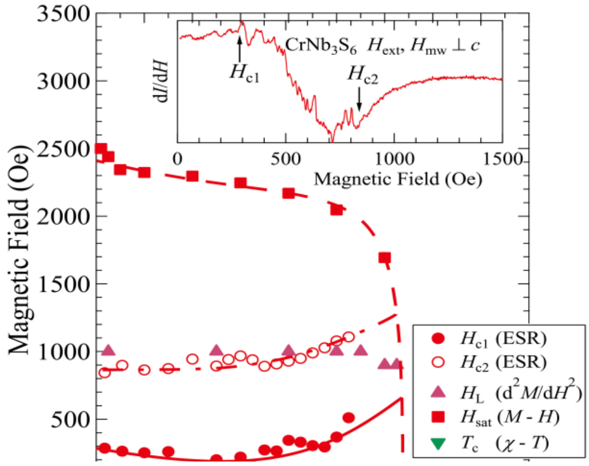

Fig. 1. *H-T* phase diagram of $CrNb_2S_6$. Inset: X-band ESR signal

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Spin structures in precursor region of uniaxial chiral magnets.

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The formation of the ordered states in noncentrosymmetric condensed matter systems occurs through a complex evolution of specific chiral magnetic modulations (*precursor states*) arising in narrow temperature intervals in the vicinity of the ordering temperatures. *Blue phases* in chiral liquid crystals [1] and so called *A-phases* in cubic helimagnets [2] are two well-known examples of such exotic transitional chiral textures.

In this contribution we investigate theoretically the precursor states in uniaxial chiral ferromagnets. Within the localized spin model [3] we have investigated a magnetic field-driven evolution of helicoids and kinks near the ordering temperature and apply our results for the analysis of precursor magnetic states in easy-plane hexagonal helimagnet $CrNb_3S_6$.

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Magnetic phase diagram of uniaxial chiral helical magnet $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$

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In the last decade, new spin-structures in chiral magnets, such as chiral soliton-lattice in hexagonal $CrNb_3S_6$ [1] and skyrmion in cubic MnSi [2], have been studied intensively because of interest in their nature and promising properties for spintronics materials.

Recently, we found a new chiral magnet $YbNi_3Al_9$. This compound crystallizes in the chiral structure of trigonal $ErNi_3Al_9$-type with space group *R*32 [3,4]. Since the Dzyaloshinskii-Moriya (DM)-vector is parallel to the *c*-axis in this crystal symmetry, the uniaxial chiral magnetic structure will appear when the magnetic easy axis is perpendicular to the *c*-axis. For $YbNi_3Al_9$, we found that only the ytterbium ion is magnetic and the moments are in the basal plane. By neutron scattering, we identified $YbNi_3Al_9$ as a chiral helical magnet with a magnetic wave vector q=(0, 0, 0.8) below an ordering temperature of T_M=3.4K [4,5].

Interestingly, the magnetic ordering temperature of $YbNi_3Al_9$ can be enhanced by the partial substitution of copper for nickel. We can replace nickel by copper up to about 6%. For $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$, an ordering temperature becomes 6.4 K which is nearly twice as high as that of $YbNi_3Al_9$. The propagation vector of $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$ is q~(0, 0, 0.4) and the formation of chiral soliton-lattice has been observed.

Thus, $YbNi_3Al_9$ is well suited to study the fundamental aspect of the asymmetric spin-orbit interaction in the rare-earth intermetallic compound. We are also interested in the similarity and difference of the chiral magnetism between 3*d*-transiton and 4*f* rare-earth metallic compounds. To study the character of phase transition from the paramagnetic (or forced ferromagnetic) to the chiral magnetic state, we measured specific heat and magnetization in magnetic field.

The magnetic phase diagrams observed by magnetization measurements for $YbNi_3Al_9$ and $Yb(Ni_{1-x}Cu_x)_3Al_9$ with x=0.02, 0.04, and 0.06, are shown in Fig. 1. The magnetic fields were applied perpendicular to the chiral axis. The ordering temperature of T_M and the critical field of H_c at which

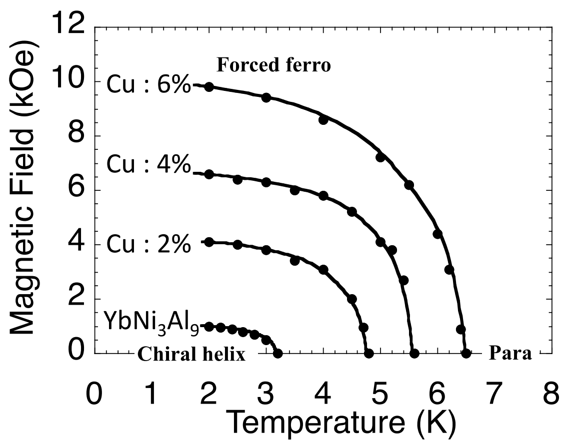

Fig. 1. The *H*–*T* magnetic phase diagrams for $YbNi_3Al_9$ and $Yb(Ni_{1-x}Cu_x)_3Al_9$ with x=0.02, 0.04, and 0.06. The magnetic fields were applied perpendicular to the *c*-axis.

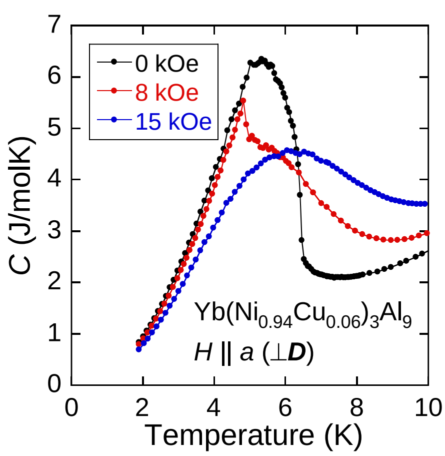

Fig. 2. Temperature dependence of specific heat for $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$ at H=0, 8, and 15kOe around T_M.

the chiral magnetic state becomes forced ferromagnetic state increase linearly with copper concentration, respectively.

Figure 2 shows the temperature dependences of specific heat for $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$ in the magnetic fields perpendicular to the helical axis. At zero field, the specific heat shows a sharp jump at magnetic transition temperature T_M=6.4 K. Above the critical field H_c=10kOe, only a broad maximum is observed at which the crossover occurs between forced ferromagnetic and paramagnetic state. It is noted that, just below H_c, the specific heat shows a characteristic sharp peak and a broad maximum in succession. The sharp peak is attributed to a transition from the chiral soliton-lattice to the forced ferromagnetic state. The broad maximum represents the crossover as described above.

We will present the magnetic phase diagrams for $YbNi_3Al_9$ and $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$ and a comparison with those of[MnSi [6] and $CrNb_3S_6$ [7].

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Session 4. Chiral couplings and phase transitions in helimagnets.

Chairman: Prof. Jun–ichiro Kishine

Functional RG analysis of Pokrovsky-Talapov model

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Greater emphasis in modern researches is focused on topological defects or vortex excitations which may occur in thin films of chiral helimagnets. One of the wellproven models in studies of the ground state of such systems is the Pokrovsky-Talapov model [1]. In this paper we investigated a possibility of the topological Kosterlitz-Thouless transition in this model by using the functional RG approach by Wetterich to find out a role of the spin vortex dynamics. Our main result is that a nonzero misfit parameter of the PT-model, which can be related with the Dzyaloshinsky-Moriya interaction, makes such a transition impossible, what contradicts the previous consideration of this problem by the nonperturbative RG methods [2].

In order to argue this conclusion the initial PT model has been reformulated in terms of the 2D theory of relativistic fermions using an analogy between the 2D sine-Gordon and the massive Thirring models [3]. In the new formalism the misfit parameter corresponds to an effective gauge field that enables to include it in the renormalization-group procedure on an equal footing with the other parameters of the theory. With the new fermionic action in hands, we apply the Wetterich equation to obtain flow equations for the parameters of the action. We demonstrate that these RG equations reproduce a KT type of behaviour if the misfit equals to zero. However, any small nonzero value of the quantity rules out a possibility of the BKT transition. To confirm the finding we develop a description of the issue in terms of the 2D Coulomb gas model using the corresponding mapping for the Pokrovsky-Talapov model. Within the approach the breakdown of the BKT scenario gains a transparent meaning. The misfit parameter results in an appearance of an effective electric field lying in the plane what prevents a formation of bound vortex-antivortex dipoles.

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Phase transitions in chiral magnets from Monte Carlo simulations

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There are strong evidences that the magnetic transition in helimagnets is of first order [1-3]. However, the nature of the phase transition in MnSi is still not well understood. This transition shows some remarkable features revealing in behavior of the specific heat, thermal expansion coefficient, temperature coefficient of resistivity and sound absorption [2], [3], presented in Fig. 1. The mentioned quantities display sharp peaks at phase transition temperature T_c followed by well-defined rounded humps on the high-temperature sides of the curves.

The origin of these enigmatic second maxima or humps is poorly understood. The corresponding attempts based on analyses of the small angle neutron scattering data strongly advance our knowledge, but still did not bring the completely satisfactory solution [4], [5]. What is certainly known now that the domain of the secondary maxima is characterized by the strong helical fluctuations as it evidenced by the diffuse neutron scattering with the intensity distributed on a sphere of radius **q**= **Q** in momentum space [4].

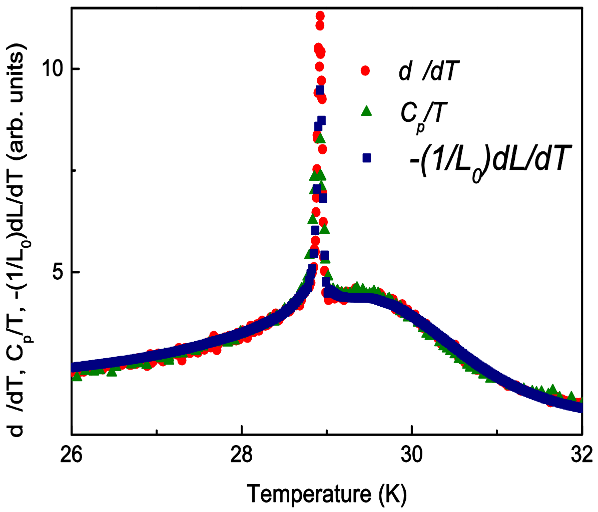

Fig. 1. Reduced specific heat divided by temperature C_p/T, linear coefficient of thermal expansion $1/L_0(dL/dT)$ and temperature derivative of resistivity $d\rho/dT$ (drawn after data of Ref. [2]).

Inspired by the successful simulation of a phase diagram of MnSi [6], we address the question on the nature of phase transition in a chiral helimagnet making use a classical Monte Carlo technique. The chiral helimagnet is modelled by the lattice spin Hamiltonian [5], [6] consisting of two competing interaction terms, Heisenberg exchange J and Dzyaloshinskii-Moriya D.

The Monte Carlo simulations well reproduce experimental situation observed in case of helical magnets MnSi and Cu_2OSeO_3. An example of an evolution of the temperature dependence of the specific heat and magnetic susceptibility with varying a ratio D/J is presented in Fig 2. The hump or shoulder in the specific heat at the high temperature side of the first order peak arises as a product of perturbation a virtual second order ferromagnetic phase transition by helical fluctuations which manifest themselves in the transient multiple spiral state. Thus the hump domain has a very complicated spin structure stipulated by the competing ferromagnetic and helical fluctuations. These fluctuations finally condense into the helical ordered phase via a first order phase transition as it indicated by the specific heat peak. This conclusion completely agrees with the analysis of the experimental thermodynamic data on the magnetic phase transition in MnSi, performed in [7].

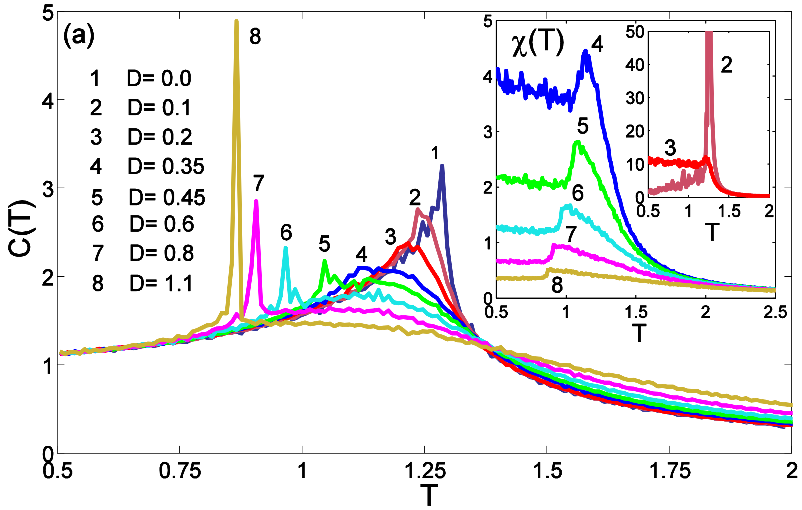

Fig. 2. Dependence of the specific heat C(T) the corresponding dependence of susceptibility χ(T) on temperature for different values of DM interaction D. The parameter J= 1 serves as a unit of temperature.

The results of calculations clearly indicate that the competing interactions are the primary factor responsible for an occurrence of first order phase transitions in helical magnets with the Dzyaloshinskii-Moriya interaction. The model demonstrates crossover from a second-order to a first-order transition with increasing D/J. With further increasing D/J one more crossover from a first-order to a second-order transition takes place in the system.

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Cascades of phase transitions in spiral magnets caused by dipolar forces

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Frustration can have a significant effect on properties of magnetic systems leading to novel phenomena which attract great interest in recent years, e.g. various spin-liquid phases, novel phase transitions and order-by-disorder phenomena. In particular, frustration changes the type of transitions to magnetically ordered phases in Heisenberg antiferromagnets (HAFs) on triangular lattices and in frustrated HAFs with a spiral magnetic ordering. The order parameter acquires additional symmetry elements which results in changing the type of the phase transition in 3D systems, to a novel pseudo-universal behavior in 3D XY systems and to the stabilization of a chiral spin-liquid phase upon cooling before the onset of Berezinskii-Kosterlitz-Thouless transition in 2D systems.

In real materials there are always weak low-symmetry spin interactions which complicate further the behavior of frustrated systems upon temperature decreasing. It is well known that dipolar forces lead to the splitting of the transition to the ordered state with 120° magnetic structure into three successive transitions in XY HAFs on the stacked triangular lattice [1]. Upon temperature decreasing there is a second-order transition from the paramagnetic (PM) phase to an incommensurate sinusoidally-modulated (ICS) state, the second-order transition to an incommensurate elliptic phase and, finally, the first-order transition occurs to the commensurate phase with the conventional 120° magnetic structure. The difference between temperatures of these three transitions is governed by the ratio of the characteristic dipolar energy and the exchange coupling constant, which is usually small in real materials. However, three successive phase transitions with these two incommensurate intermediate phases were really observed in particular triangular XY HAFs (e.g., in $RbFeCl_3$).

Frustrated Heisenberg magnets in which the spiral magnetic ordering arises due to the competition between different exchange interactions fall into the same universality classes as triangular HAFs. To the best of our knowledge, the impact of the dipolar interaction on transitions to magnetically ordered phases has not been discussed yet in such models. On the other hand, such investigation would be of particular interest due to the great attention devoted in recent years to multiferroics with spiral magnetic orderings appearing due to frustrated exchange interactions. This attention is stimulated by a possible application of such compounds in the spin-related electronics. Multiferroics MnI_2 [2] and $MnWO_4$ are promising candidates for such analysis because their exchange coupling constants are small, less than 1K, and the dominating low-symmetry interaction in these compounds is the dipolar interaction. It was found experimentally that these materials show the cascade of phase transitions upon temperature decreasing with the ICS and elliptical intermediate phases.

We develop a mean-field theory describing frustrated spiral HAFs (including HAFs on the triangular lattice) with dipolar forces near the transition from the PM phase. Phases which can arise in this model are described: the ICS phase (we assume, that this phase is energetically favorable at temperatures slightly below first critical temperature, what seems to be a usual case), the commensurate (CS) and the incommensurate spiral states (SP), elliptical phases in which two components of the order parameter are modulated with the same and with different vectors (EL1 and EL2 correspondingly). Six possible sequences of transitions to these phases are established as it shown in Fig. 1.

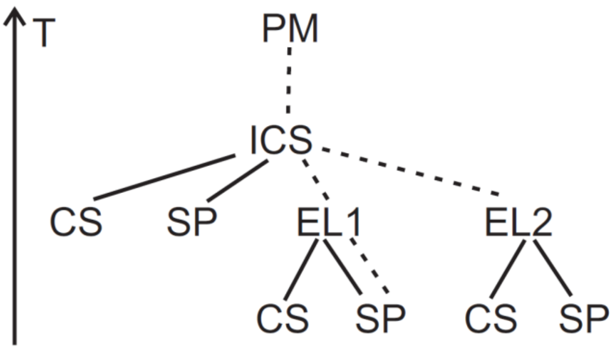

Fig. 1. Possible sequences of temperature phase transitions in frustrated spiral Heisenberg antiferromagnets with dipolar forces. Transitions of the first and of the second order are shown by solid and by dashed lines, respectively.

We describe quantitatively phase transitions in MnI_2 within the mean-field approach. MnI_2 crystallizes in a hexagonal-layered structure with lattice parameters a=4.146 Å and c=6.829 Å. Mn^{2+} ions have spin S=5/2 and g-factor g $\approx$2. This compound is in the proper screw magnetic order and has nonzero electric polarization at temperatures below 3.5 K [2]. There are three successive phase transitions in MnI2 at T_{N1}=3.95 K, T_{N2}=3.8 K and T_{N3}=3.45 K [3]. The first two are second order and the third is the first order phase transition. Between T_{N1} and T_{N2} the magnetic ordering is sinusoidal incommensurate with modulation vector $\mathbf{q}_{\text{sin}}$, Between T_{N2} and T_{N3} there is an ICS phase with modulation vector continuously moving from $\mathbf{q}_{\text{sin}}$ to $\mathbf{q}_{\text{f}}$ under temperature decreasing (see Fig. 2) and below T_{N3} it is helical also with incommensurate spiral vector.

We show that dipolar forces are indispensable for a proper description of available experimental data [3] but small symmetry-allowed easy axis and hexagonal anisotropies should be also taken into account. Besides, our analysis shows that Dzyaloshinskii-Moriya interaction (DMI) should arise in the spiral phase which is responsible for ferroelectric properties in this phase. The latter result is in accordance with recent experimental findings [2]. We successfully describe first two phase transitions at T_{N1} and T_{N2} and continuous moving of ICS phase modulation vector with temperature (see Fig. 2), but we fail to describe phase transition to the proper screw ordering, because at T $\approx$ T_{N3} effective spin is about 1.5, which indicates our mean-field approach inapplicability.

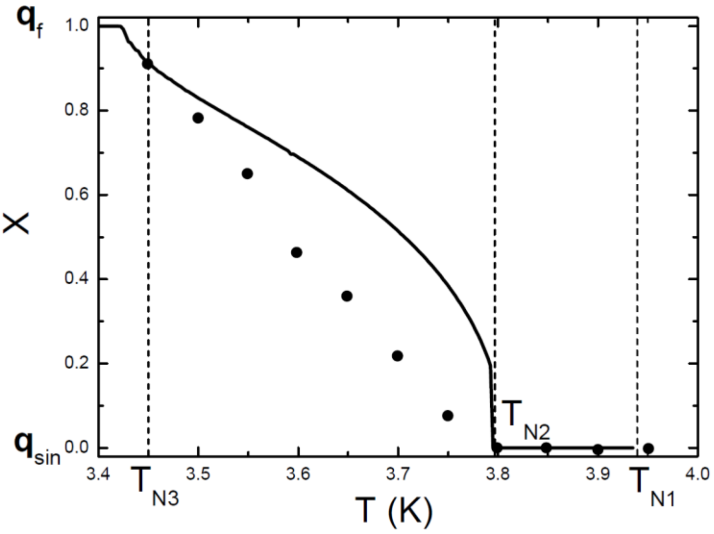

Fig. 2. Plot of X(T), which parametrizes the evolution of the modulation vector $\boldsymbol{q}$ *upon the temperature decreasing in incommensurate sinusoidal phases of* MnI_2*. At* $T_{N3} < T < T_{N2}$*, the trajectory of* $\boldsymbol{q}$ *is almost straight in the reciprocal space which starts at* $\boldsymbol{q}_{sin}$ *= (0.1025,0.1025,0.5) and finishes at* $\boldsymbol{q}_f$ *= (0.167,0,0.442). Experimental data taken from [3] are shown by circles.*

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Nucleation, instability, and discontinuous phase transitions in the monoaxial helimagnet with oblique fields

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The phase diagram of the monoaxial chiral helimagnet as a function of temperature T and magnetic field with components perpendicular (H_x) and parallel (H_z) to the chiral axis has been theoretically studied [1,2,3]. The starting point is a general Hamiltonian with long-range ferromagnetic Heisenberg and Dzyaloshinskii-Moriya interactions. The equilibrium properties are studied via the *variational mean field* approach. In the continuum limit the mean field free energy contains only a few parameters which are determined by the many parameters of the Hamiltonian.

A phase transition surface in the three dimensional thermodynamic space separates a chiral spatially modulated phase from a homogeneous forced ferromagnetic phase. The phase boundary is divided into three parts: two surfaces of second order transitions of instability and nucleation type, in De Gennes terminology, are separated by a surface of first order transitions. Two lines of tricritical points separate the first order surface from the second order surfaces. One of them, the instability tricritical line, ends at the zero field ordering transition point, which, therefore, presents tricritical behavior. In figure 1 the calculated 3D phase diagram is depicted.

The structure of the spin texture in the chiral phase and the singularities of several quantities on the transition surface are analyzed. The divergence of the period of the modulated state on the nucleation transition surface has the logarithmic behavior typical of a chiral soliton lattice. The specific heat diverges on the nucleation surface as a power law with logarithmic corrections, while it shows a finite discontinuity on the other two surfaces. The soliton density curves are described by a universal function of H_x if the values of T and H_z determine a transition point lying on the nucleation surface; otherwise, they are not universal.

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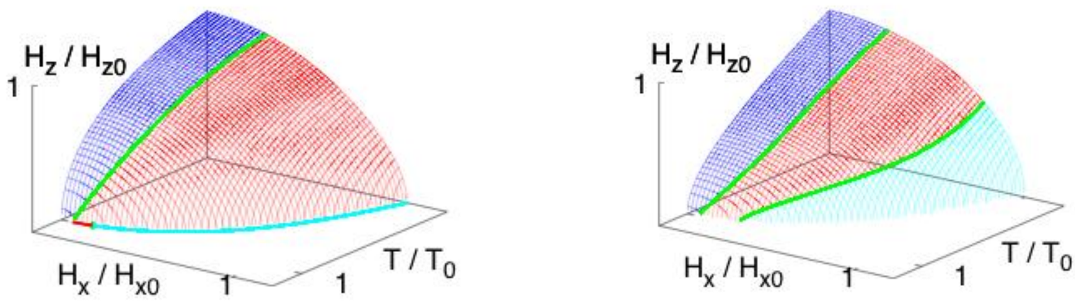

Fig. 1 3D phase diagram without (left) and with (right) single-ion anisotropy (γ=2.58). The second order transitions take place on the dark blue (*instability*) and light blue (*nucleation*) portions of the transition surface. On the red portion the transitions are of first order. The tricritical lines separating the first order surface from the two second order surfaces are displayed in green.

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Session 5. Phase transitions in helimagnets.

Chairman: Dr. Yoshihiko Togawa

Phase transition of MnSi under magnetic field: A SANS and Neutron Spin Echo Study

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The reference chiral helimagnet MnSi has been the first system where skyrmion lattice (SkL) correlations have been reported [1]. At zero magnetic field the transition at Tc to the helimagnetic state is of first order. Above Tc, in a region dominated by precursor phenomena, neutron scattering shows the building up of strong chiral fluctuating correlations that spread homogeneously over the surface of a sphere with radius $\tau = 2\pi/l$, with ℓ the pitch of the helix [2]. It has been suggested that these fluctuating correlations drive the helical transition to first order according to a scenario proposed by Brazovskii for liquid crystals [3]. We present a comprehensive neutron scattering study under magnetic fields, which provides evidence that the sharp first order transition persists up to $B \approx 0.4\,T$ whereas the fluctuations above Tc become less intense and start to concentrate along the field direction already for $B \gtrsim 0.2\,T$, as shown in Fig. 1. It appears that the precursor phenomena and the strong fluctuating correlations do not provide an explanation for the first order phase transition in cubic helimagnets. Other approaches are thus required to account for both the precursor phenomena and the first order of the helical transition.

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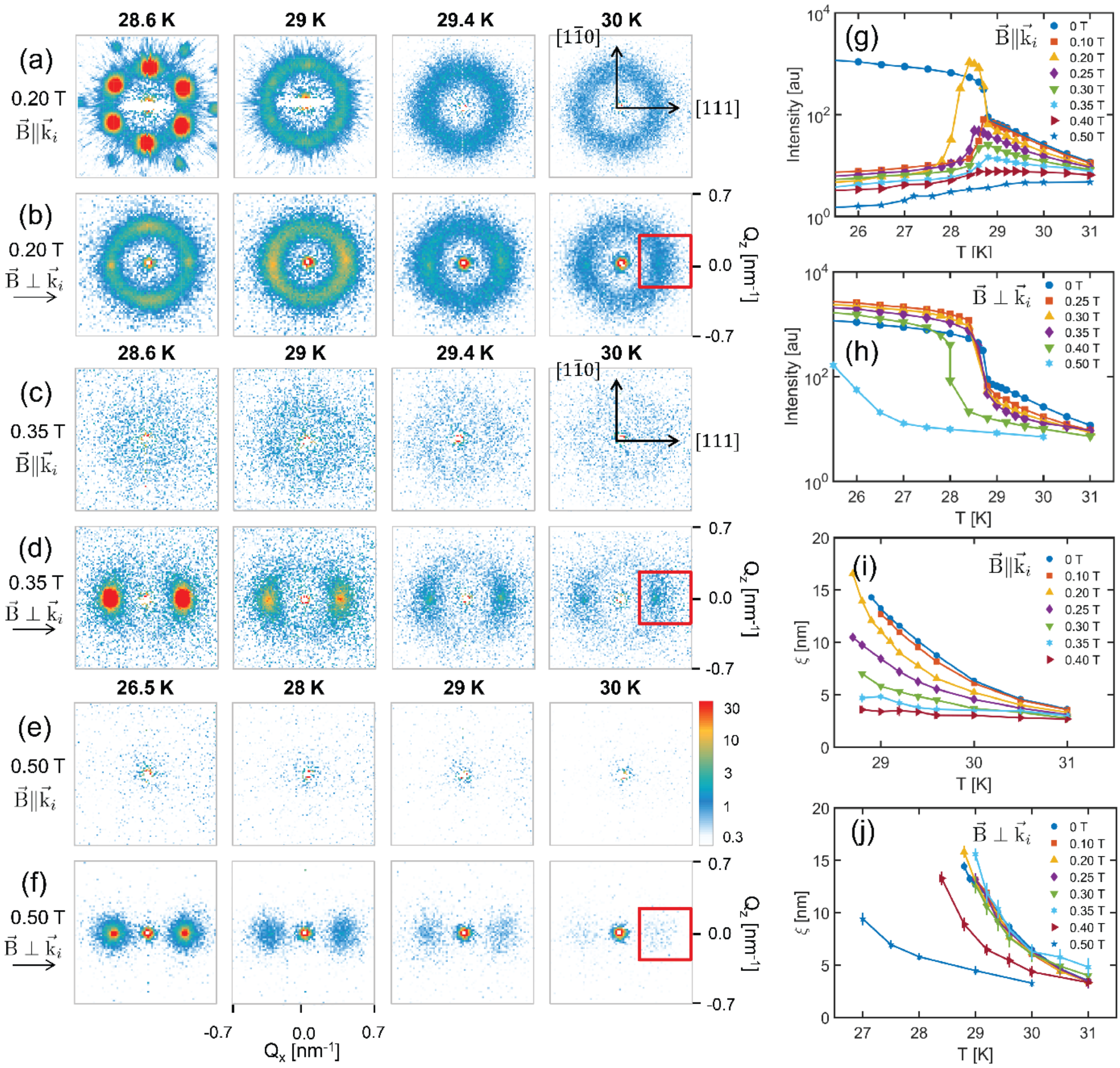

Fig. 1: SANS scattering patterns obtained for a magnetic field of 0.20 T (a)-(b), 0.35 T (c)-(d) and 0.50 T (e)-(f), where the field was applied parallel to the neutron beam ($\vec{B} \parallel \vec{k}_i$) and perpendicular to it ($\vec{B} \perp \vec{k}_i$). The red squares illustrate the angular acceptance of the NSE experiments. The temperature dependence of the total scattered intensity obtained by summing the entire detector is displayed in Panel (g) for several fields along the neutron beam and in Panel (h) for fields perpendicular to it. Panel (i) and (j) show the temperature dependence of the correlation length for magnetic fields along and perpendicular to the neutron beam, respectively

On the phase diagram of the itinerant helical magnet MnSi at strong magnetic fields

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Phase diagram of the itinerant helical magnet MnSi at strong magnetic fields was investigated with a series of heat capacity [1,2], thermal expansion, forced magnetostriction [3] and ultrasound speed measurements [4].

The helical phase transition in MnSi demonstrates some remarkable features, which are not well understood. The heat capacity, thermal expansion coefficient, temperature coefficient of resistivity, elastic moduli and absorption coefficient of MnSi form rounded maxima or minima at temperature slightly above the first order phase transition peaks. These rounded features are flattened and spread out by the application of a magnetic field, which indicates spin fluctuations as responsible for this effect.

We argue that all these rounded maxima (minima) identify a smeared second order phase transition. An initial thought that the smearing occurs due to intrinsic imperfections of MnSi appeared to be not quite correct. The helical fluctuations smear a virtual ferromagnetic second order phase transition, which result in the features observed in experiments. The first order phase transition in MnSi arises as a result of competing two interactions, which are: ferromagnetic exchange and Dzyaloshinskii – Moriya interactions. The competing produces so powerful fluctuations that the system cannot proceed continuously into the ordered phase and has to do it by a discontinuous way [5].

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Dissipation Phenomena and Magnetic Phase Diagram of Cu_2OSeO_3

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We present an investigation of the magnetic field-temperature phase diagram of Cu_2OSeO_3 based on DC magnetization and AC susceptibility measurements covering a broad frequency range of four orders of magnitude (0.1 Hz to 1 kHz). These measurements are complemented by small angle neutron scattering (SANS).

The frequency dependence of the susceptibility, between the helical and conical phases at B_{C1} and between the conical and A-phases, is governed by almost macroscopic relaxation times, which reach some milliseconds and may be attributed to rearrangements of large magnetic volumes [1]. The strongly non-exponential relaxation bears similarities with spin glasses and is in line with the glassy behavior reported by electron microscopy in Cu_2OSeO_3 [2] and other systems with similarly long helices [3]. These dynamical phenomena could be at the origin of the different phase boundaries reported in the literature not only for Cu_2OSeO_3 but also for other systems of the same family including the reference chiral magnet MnSi.

Below 50 K, the transition from the helical to the conical phase splits to two adjacent B_{C1} lines. Furthermore, qualitatively different phase diagrams have been obtained by applying the magnetic field B along the easy <100> or the hard <110> crystallographic directions (Figure 1). In particular, close to transition from the conical to the field-polarised state at B_{C2}, a strong χ'', the imaginary component of the susceptibility, appears but only below ~30 K and when B is applied along <100>. These results are complemented by SANS, which reveals the appearance of scattered intensity outside the conical Bragg peaks, close to B_{C2} but only below ~30 K and for B//<100>. These results will be discussed in view of theoretical predictions for the influence of the cubic anisotropy on the phase diagram of Cu_2OSeO_3 [4, 5].

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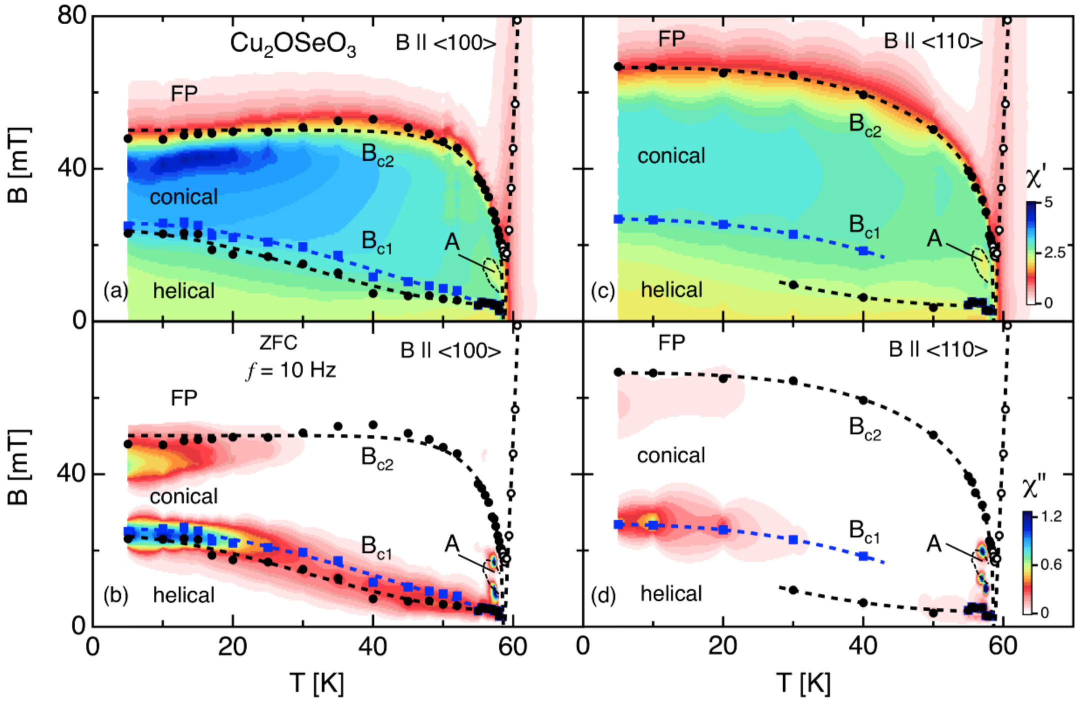

Figure 1: Contour plots of the real and imaginary components of the susceptibility, χ' and χ'' respectively, displayed versus temperature and magnetic field at *f* = 10 Hz. The data have been collected by Zero Field Cooling (ZFC) the sample through T_C and then applying the magnetic field B//<100> in panels (a) and (b), and B//<110> in panels (c) and (d). The phase boundaries B_{C1}, B_{A1}, B_{A2} and B_{C2} are shown and below ~50 K the B_{C1} line splits in two. In the contour plots, we identify the following phases: helical, conical, A for the A-phase and FP for the field polarised one. The units for χ' and χ'' are 10^{-5} and 10^{-6} m^3/mol_{Cu} respectively.

Metastability and Hysteresis in Chiral Helimagnet

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The order of the phase transition is one of the fundamental problems in the field of the uni-axial chiral helimagnets. Some experimental [1-3] and theoretical [4,5] studies have suggested the existence of the first-order phase transition. A Monte Carlo study [6], on the other hand, implies a continuous phase transition for the whole magnetic field range with the change of critical exponents from the one for the three-dimensional XY model at low field to a different one with a strong divergence of the specific heat near the transition temperature at high field. It is desirable to resolve the discrepancy between these studies. For this purpose, we investigate the phase transition of a three-dimensional chiral helimagnet on a lattice model using the mean-field theory. We evaluate the height of the energy barrier which creates the double minimum structure in the free-energy profile in the first-order transition region. By comparing the height of the energy barrier with thermal energy (i.e. $k_B T$), we elucidate the condition in which the first-order transition signature is observable.

We also analyze a finite-size effect on the physical properties of the chiral helimagnets. Experimental studies have shown hystereses in the magnetization [1,2,7] and magneto-resistance [8,9] using small $CrNb_3S_6$ samples, which often involve step-like behavior. Although these hystereses can be related to the finite-size effect, the relation between the finite-size effect and hysteresis has not been investigated theoretically so far. Using various boundary conditions, we show that many local minima appear in the free-energy profile as the magnetic field increases. By simulating the decreasing external field process numerically, we clarify the relations between these local minima and hystereses.

We thank M. Mito and H. Ohsumi for informative discussions about experimental studies and thank A. N. Bogdanov and A. O. Leonov for critical discussions about the phase diagram. The computations in this work have been done using the facilities of the Supercomputer Center, the Institute for Solid State Physics, the University of Tokyo. This work was supported by JSPS KAKENHI Grant Number JP16J00091. This work was also sup- ported by the Center for Chiral Science in Hiroshima University, and by JSPS Core-to-Core Program, A. Advanced Research Networks.

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Session 6. Spin excitations in helimagnets with DM interaction.

Chairman: Dr. Arsen Gukasov

From helimagnons towards non-reciprocal spin-waves in MnSi

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MnSi is a chiral magnetic compound hosting a plethora of different magnetic phases. Among the magnetic orders are a helimagnetic, a conical, and a field-polarised ferromagnetic phase, with the most prominent of them being the A-phase featuring a hexagonal Skyrmion lattice [1]. The different magnetic phases originate from a competition of three distinct interactions: the ferromagnetic exchange, the Dzyaloshinsky-Moriya interaction, and the weak crystal electric field [2].

The dispersion relation in the helimagnetic phase was mapped out by Janoschek *et al.* [2] in a multi-domain sample, where the magnetic domains are aligned along the <111> directions. Experiments by Kugler *et al.* [3] determined the dispersion in a single-domain sample. The experimental results are in excellent agreement with the helimagnon spectra that have been derived in terms of a universal Ginzburg-Landau theory, which depends on only a few macroscopic material parameters.

For the present work, we determined the full field-dependence of the helimagnon dynamics towards the field-induced ferromagnetic regime. In the helimagnon phase, the dispersion branches are symmetric with respect to momentum and energy transfer. For increasing fields, the spectral weights of the magnon branches shift towards an increasingly asymmetric dispersion (Figure 1). The results constitute a non-reciprocal spin-wave dispersion, for which magnons are created with different energies than they are annihilated. In MnSi, such an effect could first be observed by Grigoriev *et al.* [4] and by Sato *et al.* [5] for one of the magnon branches at the border of the phase transition.

We furthermore observed a significant increase in the magnon linewidths close to the ferromagnetic phase transition, indicating anharmonic damping effects. Both these results necessitated a modification to the universal helimagnon theory [2,3]. By calculating the four-dimensional convolution integral of the modified theory [6] and the instrumental resolution function we could obtain an excellent agreement with our experimental data sets.

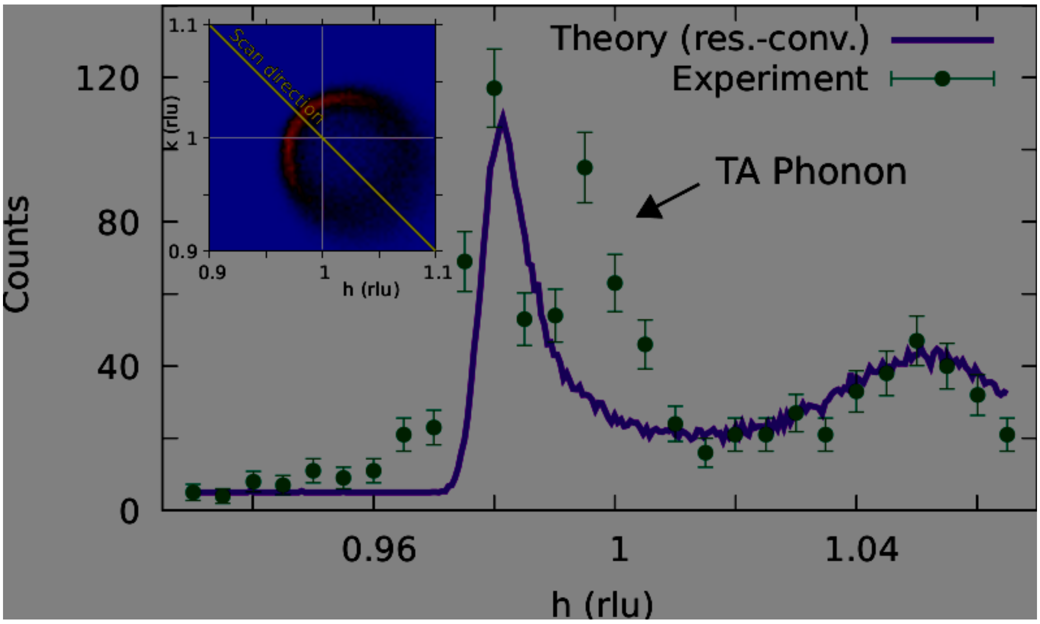

Figure 1*:* Const.-*E* scan in the field-induced ferromagnetic phase. For increasing magnetic fields, the helimagnon dispersion becomes more and more asymmetrical. The line shows a four-dimensional convolution of our theoretical model [6] with the instrument resolution. The inset shows a const-*E* cut of the resolution-corrected model and the scan direction.

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Spin waves in full-polarized state of Dzyaloshinskii-Moriya helimagnets $Mn_{1-x}Fe_xSi$: small-angle neutron scattering study

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An archetype compound MnSi is known to order in the helical spin structure below T_C. The substitution of manganese by iron in the isostructural solid solutions $Mn_{1-x}Fe_xSi$ suppresses the helical spin state. The neutron scattering studies together with magnetic data and specific heat measurements discovered a quantum critical point (QCP) corresponding to the suppression of the spin spiral phase with long-range order (LRO) in $Mn_{1-x}Fe_xSi$. This QCP located at x_{c1} = 0.11 – 0.12 is, however, hidden by a spin helix short-range order (SRO) appeared below T_{DM} [1]. The critical temperatures T_C and T_{DM} decreases with x and can be extrapolated to 0 at x = 0.12 and 0.17, respectively.

We develop the technique to study the spin wave dynamics of the full-polarized state of the Dzyaloshinskii-Moriya helimagnets by polarized small-angle neutron scattering [2]. We have experimentally proven that the spin waves dispersion in this state has the anisotropic form. We show that the neutron scattering image displays a circle with a certain radius, which is centered at the momentum transfer corresponding to the helix wave vector in helimagnetic phase k_s, which is oriented along the applied magnetic field **H**. The radius of this circle is directly related to the spin-wave stiffness of this system. This scattering depends on the neutron polarization showing the one-handed nature of the spin waves in Dzyaloshinskii-Moriya helimagnets in the full-polarized phase.

We perform the measurements of the spin-wave stiffness A and its temperature dependence for the series of the compounds: MnSi, $Mn_{1-x}Fe_xSi$ with x = 0.03, 0.06, 0.09, 0.10. The spin-wave stiffness A for the Fe-doped compounds does not change with temperature up to the critical temperature T_C showing that the criticality originates from the source different from the enhancement of the spin-wave amplitude. In order to reveal the link between the spin-wave stiffness and the critical temperatures, we plotted A of the different $Mn_{1-x}Fe_xSi$ compounds against the critical temperature T_C and against the temperature T_{DM}. It appears that the spin wave stiffness is linearly proportional to the temperature T_{DM}, but not to T_C. This observation implies that the ordering in the system is not trivially determined by the isotropic exchange A but is additionally destabilized by another mechanism. This additional source of the instability can naturally be assigned to the DM interaction, which strength can be roughly estimated via the helix wave vector k.

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Spin wave propagation in a chiral monoaxial crystal $CrNb_3S_6$

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In a magnetic crystal with structural chirality, chiral spin soliton lattice (CSL) emerges as the ground state when a magnetic field (*H*) is applied perpendicular to helical axis. The CSL is a spin phase object of a nonlinear periodic array of 2π kinks and exhibits phase coherence over macroscopic length scale. Materials with such properties are excellent candidates for spintronics applications [1] as the CSL phase may be seen as a 'naturally' occurring nanostructured system whose magnetic texture is highly reconfigurable and topologically protected by the crystalline structure [2, 3]. In this respect, it is very interesting to examine the spin wave properties in materials exhibiting the CSL structure [4, 5, 6]. We present results on the spin wave propagation conditions of micro-sized lamellae of the chiral monoaxial helimagnetic crystal $CrNb_3S_6$. In these experiments, a microwave antenna (emitter) generates a spatially non-uniform field with well-defined wavevector emission spectra, k_i, which excites a spin wave packet on one end of the micro-sized crystal. The spin wave packet propagates in the direction perpendicular to the axis of the emitter, towards the other end of the crystal, and is efficiently detected by a second antenna (receiver) [7]. We investigate the propagation conditions in the directions perpendicular *(I)* and parallel *(II)* to the helical axis of the crystal. The non-reciprocal behavior, $\omega(k_i) \neq \omega(-k_i)$, is examined by reversing the propagation direction at both positive and negative applied magnetic fields. In *(I)*, magnetostatic surface spin waves are excited, in agreement with Damon-Eshbach (*k* perp. *M*) configuration [8]. Here, magnetic field tunable spin wave intensity and frequency non-reciprocity are found and their origin is attributed to combined asymmetric interface conditions and DMI [9]. In *(II)* where *k* is parallel to both *M* and *H*, backward volume spin waves are excited [8]. Here, intensity and frequency non-reciprocity are observed. Interestingly, it is found that the helical phase enables enhanced propagation of the spin waves. These results may further the development of highly efficient, field tunable and non-reciprocal spin wave devices.

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Dzyaloshinskii-Moriya Helices and Magnetic Field

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Interaction of the DM helices with magnetic field is considered in the classical approximation. The helix feels the field component which is perpendicular to the spin rotation plane. Other component can destroy the helix giving a collinear structure. Changing the field one can modify the form of helix, including direction and value of its wave vector.

The surface ferromagnetic and antiferromagnetic layers and the simplest multiferroic model are considered as examples.

Spin-wave chirality and its manifestation in antiferromagnets

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After the discovery of a new conservation law for the Maxwell's equations in vacuum by Lipkin [1], it was realized that not only geometrical objects, but also fields could be characterized by chirality. In particular, free electromagnetic field can be characterized by conserving pseudoscalar, which is even under time reversal and odd under spatial inversion. These properties are consistent with the concept of "true chirality" proposed by Barron, which is opposite to "false chirality" that breaks time-reversal symmetry [2]. In the literature, this quantity was dubbed optical chirality, or "zilch". Recently, this quantity attracted considerable interest after the discovery of Tang & Cohen [3]. They demonstrated that in chiral metamaterials optical zilch determines the asymmetric part of the energy absorption rate. Later it was established that electromagnetic field in vacuum remains invariant under the 8-dimensional Lie algebra of nongeometric symmetries [4]. This leads to an infinite number of integro-differential conservation laws, and, in particular, to the conservation law of zilch.

In this presentation, we are going to discuss how the concept of optical chirality can be generalized on spin waves in antiferromagnets – another system that hosts elementary excitations doubly degenerated with respect to polarization. For this purpose, we will first establish a formal correspondence between linearized Landau-Lifshitz equations for sublattice magnetizations and the Maxwell's equations for electromagnetic field in the Silberstein-Bateman formulation. From this analogy, we will derive nongeometric symmetry transformations for spin waves and define conserving spin-wave chirality density, which is a direct magnetic counterpart of optical zilch. We will demonstrate that similar to chiral metamaterials [3], this quantity determines the asymmetry in the spin-wave energy absorption if we properly break chiral symmetry inside the material. For this purpose, we propose to use spin current injection as a potential symmetry breaking mechanism.

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Session 7. Exotic spin structures (skyrmions) - I.

Chairman: Dr. Ted Monchesky

Different Skyrmion Lattice States in the *A*-Phase of MnSi Revealed by Magnetoresistance Probing

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The magnetic scattering of charge carriers is known to dominate in MnSi under negligible Boltzmann contribution to magnetoresistance (MR) [1], so that this physical parameter happens to be very sensitive to the magnetic structure. Therefore studying of the MR anisotropy may bring additional information which is hardly accessible in direct structural studies. In the present work, we apply MR as a probe of the skyrmion lattice (SL) state in the *A*-phase of MnSi. The precise measurements of the magnetoresistance angular dependences inside and around the *A*-phase domain in bulk MnSi single crystals are carried out [2]. It is demonstrated that the SL in MnSi is not uniform. In the area inside the *A*-phase, which is common to all crystallographic directions (*A*-phase core) the magnetoresistance becomes isotropic, whereas either in the surrounding part of the *A*-phase, or in the other magnetic phases, the magnetoresistance is anisotropic and the strongest magnetic scattering occur when external magnetic field is aligned along [001] or [00-1] directions. The analysis of the MR data allows concluding that *A*-phase is not magnetically homogeneous and there is well-defined magnetic transition between the *A*-phase core and the rest of the *A*-phase. We argue that the observed structure of the *A*-phase is caused by the presence of two different types of the SL states, where dense skyrmion state of the *A*-phase core is built from individual skyrmions analogues to Abrikosov-type magnetic vortexes. The obtained structure of the *A*-phase was missed in all previous studies and should provide a new look on the problems of skyrmion stability in the 3D case, melting of the skyrmion lattice and alternative skyrmion-based interpretations of the *A*-phase nature.

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Unraveling the coupling between skyrmion and crystallographic lattices

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The observation of skyrmions and their lattices lead to a great interest in this form of topological protected non-trivial spin textures [1]. These skyrmions appear in non-centrosymmetric structures and have particle-like properties forming lattices in a small pocket in the magnetic field – temperature phase diagram just below the critical temperature T_c, which has been identified as the A-phase. Magnetic susceptibility and Small Angle Neutron Scattering (SANS) data indicate the existence of different pockets within the A-phase [2-3], that are related with the orientations of skyrmion lattices with respect to the crystallographic lattices [3].

We present a systematic SANS study that unravels this coupling in the archetype chiral magnet MnSi and the multiferroic Cu_2OSeO_3. We show that the orientation of a skyrmion lattice depends not only on the magnetic history but also on the field orientation with respect to specific crystallographic directions. In both systems, skyrmion lattices are stabilized along two main crystallographic directions. Depending on the magnetic history, the lattices may relax from one orientation to the other over macroscopic time scales that can be followed by SANS in real time. The results show the importance of the coupling between skyrmion and crystallographic lattices and highlight its importance for the stabilization of skyrmion lattices. This coupling could provide a key to control and manipulate skyrmions for future applications.

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Topological spin textures probed by coherent resonant soft X-ray scattering

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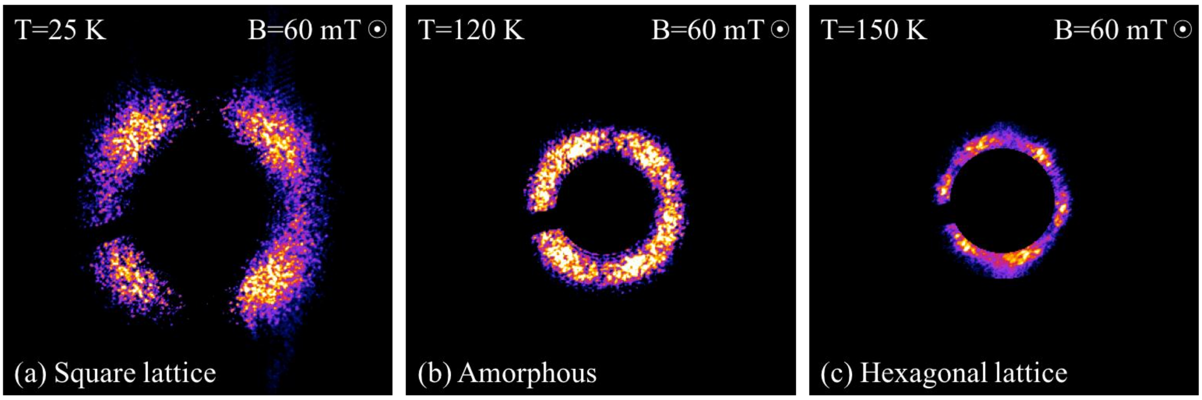
Lensless imaging with coherent hard and soft X-rays is a rapidly establishing technique, which has been successfully performed for various investigations in field of condensed matter physics [1]. One of the promising applications of coherent soft X-ray beams is imaging of local magnetization of magnetic specimens [2]. In soft X-ray regime, by exiting the 2p state to the 3d state of transition-metal atoms, it is possible to probe a magnetic ordering in wide-angle diffraction [3,4] or small-angle scattering geometry [5]. Polarization-dependent (or dichroic) resonant soft X-ray scattering (RSXS) can be successfully combined with the coherent diffraction approaches, such as iterative phase retrieval, Fourier transform holography (including holography with extended reference, so-called HERALDO) and ptychography for the lensless real-space imaging of local magnetic moment at the scale from a few tens nanometers to a few microns. The advantage of coherency-based imaging methods compared to conventional scanning transmission soft X-ray microscopy is much more flexible sample environment, including cryogenic equipment and magnetic fields.

We employ the coherent RSXS to investigate the magnetic ordering of chiral non-centrosymmetric compounds. Helical magnetic ordering appears in weak ferromagnets due to the interplay between exchange interaction, Dzyaloshinskii-Moriya interaction and anisotropy. By application of moderate magnetic field, helical structure can be transformed to the ordered lattice of topologically protected vortex-like spin configurations, so-called skyrmions (SkX). In past decade, SkX has been observed in bulk crystals of chiral B20 compounds by means of small-angle neutron scattering (SANS) [6–8]. Alternatively, Lorentz transmission electron microscopy (LTEM) has been employed for the real-space imaging in case of the thin plates and thin films [9,10]. On the other hand, recent developments of the synchrotron radiation sources and X-ray free-electron laser facilities provide X-ray scattering methods several advantages compared to the neutron scattering and electron microscopy: high brilliance of the X-ray sources, wide energy range, spatial coherence and short time length of the pulses. In example, the typical characteristic length scale of the skyrmion lattice in B20 compounds is ranging from several tens to hundreds of nanometers, what is corresponding to the small-angle scattering region for the soft X-rays with energy matching the $L_{2,3}$ absorption edges of transition metals. Thus, coherent soft X-ray scattering allows simultaneous reciprocal and direct space information on local magnetic texture with elemental selectivity.

In present work, we performed an element-specific soft X-ray study of non-centrosymmetric magnets FeGe, $Co_8Zn_8Mn_4$ by means of coherent diffraction imaging and HERALDO. As an example, a coherent RSXS patterns measured for $Co_8Zn_8Mn_4$ at different temperatures during field



cooling are shown in Fig. Coherent diffraction speckles are indicating transition from hexagonal to square skyrmion lattice (Figure a, c) via intermediate amorphous state at T=120 K (Figure b). Real-space image of the magnetic texture was reconstructed from the speckle patterns by iterative phase-retrieval algorithm. Results of the RSXS experiment are consistent with previous SANS [11] (Fourier-space patterns) and LTEM experiments [12] (real-space texture). Moreover, by using element-specific imaging in case of multicomponent compounds, like in case of CoZnMn, we can formulate a quantitative criterion for reliability of the resulted real-space reconstructions.

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Stability of skyrmionic textures in cubic helimagnets and the role of thermal fluctuations

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The low temperature phase diagram of the cubic helimagnet is studied as a function of temperature and magnetic field by the saddle point method including quadratic thermal fluctuations. The well-known saddle point solutions are the ferromagnetic state (FM), the conical helix state (CH) and the skyrmion lattice (SKL) obtained in the circular cell approximation [1]. They can be stable, metastable, or unstable. At zero temperature, where the fluctuations do not contribute to the free energy, a critical field (H_0) separates the $H < H_0$ phase, where the CH is the stable state and the FM state is unstable, from the $H > H_0$ phase, where the opposite happens. The SKL is metastable for $0.55 < H/H_0 < 0.8$ and unstable elsewhere [2]. Isolated skyrmions are unstable for $H < H_0$ and metastable for $H > H_0$ [2].

The effect of the thermal fluctuations changes the scenario [2]. First, the period of the conical helix is renormalized (Fig 1 left), increasing with the temperature and/or magnetic field. Second, for fixed temperature the CH phase looses the stability at a field value $H_c(T)$ at which the FM state is still unstable. Thus, there exist a region in the phase diagram where both the CH and the FM state are unstable, and a *intermediate* phase emerges between the low-field CH phase and the high-field FM phase (Fig. 1 right). The transition from the CH to the *intermediate* phase is discontinuous. The nature of the intermediate phase is under investigation, but the preliminary analysis points out that the SKL becomes the stable state at least in some region of the *intermediate* phase. In other regions of the intermediate phase a conical helicoid, with a propagation vector tilted with respect to the magnetic field [3], is the best candidate to be the stable state.

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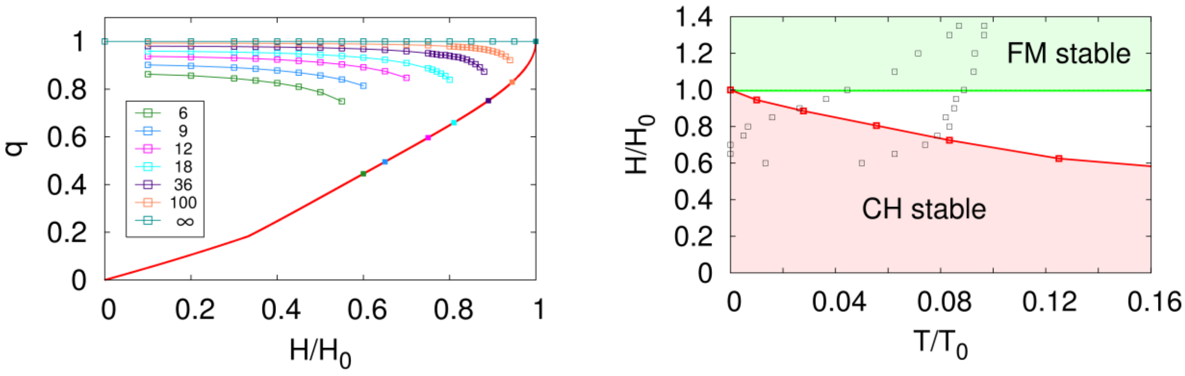

Fig. 1 Left: CH wave-number as a function of H/H_0 for several values of T_0/T, where T_0 is a characteristic temperature of fluctuations; on the red line the CH attains the FM state since the cone angle vanishes. Right: low T phase diagram. Within the contour signaled by the black squares the SKL is metastable. Hence, in some region within the intermediate phase (white) the SKL is expected to be the ground state.

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Role of the critical helix fluctuations in stabilization of the skyrmion lattice in MnSi

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The temperature evolution of the spin structure of MnSi is studied close to T_C under applied magnetic field. Specially chosen geometry of the small angle neutron diffraction experiment allowed us to simultaneously visualize three different magnetic states: (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 skyrmion lattice with $\mathbf{k}_h \perp \mathbf{H}$.

We demonstrate that both conical and skyrmion lattices can be observed above the critical temperature T_C = 29 K, having critical spin helix fluctuations on a background. The conical lattice can be traced up to the temperatures, where the correlation length ξ is of order of the helix period d_s. The skyrmion lattice is localized near T_C and related to the helical fluctuations with the correlation length $\xi \approx 2d_s$ and the propagation vector perpendicular to the field axis $\mathbf{k}_f \perp \mathbf{H}$. We argue that these helical fluctuations can be considered as defects generating and stabilizing the skyrmion lattice.

Neel-type Skyrmion lattice formation in a new class of polar magnet

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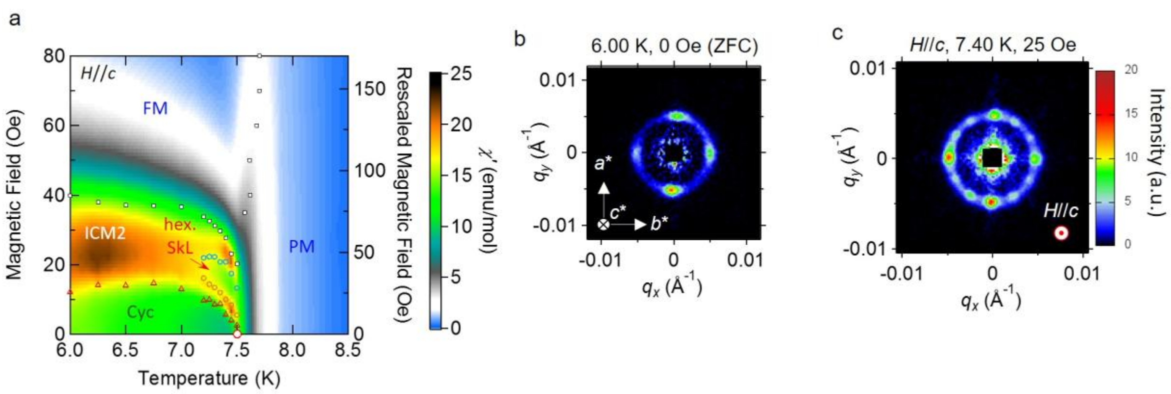
$VOSe_2O_5$ has been known to form a tetragonal polar lattice with the space group *P*4*cc* and to exhibit a ferrimagnetic-like transition at T_C = 7.5 K [1-3]. We synthesized the single crystal and performed the detailed magnetization study to reveal the versatile magnetic phases in a low-field region (H < 100 Oe) including the "A phase" close to the T_C (see the *H-T* phase diagram determined by the ac susceptibility measurement in Fig. a). We perform the SANS investigation and obtain the experimental evidence for the phase transition between cycloidal helimagnetic phase and the skyrmion lattice phase to demonstrate the Neel-type skyrmion lattice formation [4] in a new type of polar magnet.

Figure b shows the SANS pattern at 6 K in zero applied field. Clear four-spot pattern along the equivalent *a* and *b* axes was observed indicating the magnetic modulation with the long-wavelength (q ~ 0.005 A^{-1}). Domain rearrangement with *H*//*a* favoring $q \perp H$ configuration was observed suggesting the cycloidal helimagnetic order with the spin spiral plane perpendicular to the *c* plane. Figure c shows the SANS pattern in the A phase (7.4 K, 25 Oe). Clear twelve-spot pattern was observed indicating the multidomain of skyrmion-lattice in this phase as observed in $Co_8Zn_8Mn_4$ [5].

Acknowledgement: We greatly thank Dr. D. Hashizume for the support of X ray diffraction to co-align the single crystals for the SANS measurement.



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Session 8. Theory of DMI effect on the magnetic structure.

Chairman: Dr. Dmitry N. Aristov

Individual Magnetic Vortices Investigated by Nanosquid Magnetometry

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We present the investigation of individual magnetic vortex states developed in nanodiscs by means of nanoSQUID magnetometry. For this purpose, ultra-sensitive YBCO and Nb nanoSQUIDs operative in strong magnetic fields have been used. YBCO SQUIDs are based on submicron grain boundary junctions and have been patterned by focused ion beam milling, whereas Nb SQUIDs consist of SNS sandwich-type junctions based on Nb/HfTi/Nb technology patterned by e-beam lithography. Magnetic nanodiscs have been patterned at precise positions over the sensor's surface with nanometric resolution by means of focused electron beam induced deposition of amorphous cobalt. Electron holography and Lorentz microscopy have been used to confirm and inspect the existence of flux-closing magnetic states in similar discs of different sizes and aspect ratios. The impressive spin sensitivity (few $\mu_B/Hz^{1/2}$) reached with our nanoSQUIDs has enabled the detection of the tiny magnetic stray field created by magnetic flux-closing structures. The possibility of operating the sensors upon remarkably large in-plane magnetic fields (up to one Tesla) allows investigating the nucleation, displacement and annihilation of the magnetic vortex that leads to the magnetization reversal. We have performed an in-depth investigation of these thermally assisted nucleation/annihilation processes thanks to the large range of operation temperatures of the nanoSQUID (mK – 60 K). These studies serve to shed light on the nature and magnitude of the energy barriers separating the vortex and the saturated states, the nucleation/annihilation fields and switching times. These properties are essential for the development of magnetic memories and devices based on vortex states.

Topological domain walls in helimagnets

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The Dzyaloshinskii-Moriya interaction in chiral magnets stabilizes a magnetic helix with a wavelength set by the spin-orbit coupling. We study domain walls of helimagnetic order both theoretically and experimentally using micromagnetic simulations and magnetic force microscopy studies on surfaces of FeGe. We find that such domain walls are distinctly different from those in ferromagnets and rather similar to grain boundaries of liquid crystals. Three types of domain walls are realized depending on the relative domain orientation: a curvature wall, a zig-zag disclination wall and a dislocation wall. Disclinations are vortex defects in the helix axis orientation, and they can be combined to form dislocations. We discuss the topological skyrmion charge associated with these defects, and we demonstrate that domain walls of helimagnetic order can carry a finite topological charge on average. As a consequence, they can be manipulated by spin currents and contribute to a topological Hall effect.

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Session 9. Exotic spin structures (skyrmions) - II.

Chairman: Dr. Alexander S. Ovchinnikov

Stability of skyrmion and interaction of magnons

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The stability of a single Belavin-Polyakov (BP) skyrmion in isotropic Heisenberg ferromagnet is studied. Such skyrmion is higher in energy than the uniform ferromagnetic state and is thus metastable. Starting from the lattice model in two spatial dimensions and using Maleyev-Dyson representation for spin operators, we examine the effects of magnon-magnon interaction for two quantities at T=0. First we discuss the self-energy corrections to magnon energy. Second we analyze the two-particle Green's function and possible bound states of two magnons. The simplicity of the model makes possible full analytic treatment of all relevant processes. We found that the magnons remain well-defined quasiparticles with a finite lifetime. The bound states of two magnons are suppressed near the skyrmion, although they are not excluded far away from it. A resonance for the magnons of dilational mode in the vicinity of BP skyrmion is found, which leads to a redistribution of the spectral weight. Thus BP skyrmion as the classical topological object is not destroyed by quantum fluctuations.

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Skyrmion spin-wave resonances in ferromagnetic film with spatially modulated perpendicular anisotropy

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We present the theoretical studies of ferromagnetic resonance (FMR) in the array of magnetic skyrmions stabilized in ferromagnetic film with spatially modulated perpendicular anisotropy. Recently we have shown the possibility of the experimental realization of such skyrmion arrays in the Co/Pt multilayer locally irradiated with He focused ion beam [1]. The sample was a square lattice of cylindrical areas with reduced anisotropy (Fig. 1). In present talk we focus our attention on spin-wave resonances in such system motivated by new possibilities of the local detecting of FMR modes by the novel methods of magnetic resonance force microscopy (MRFM) [2,3].

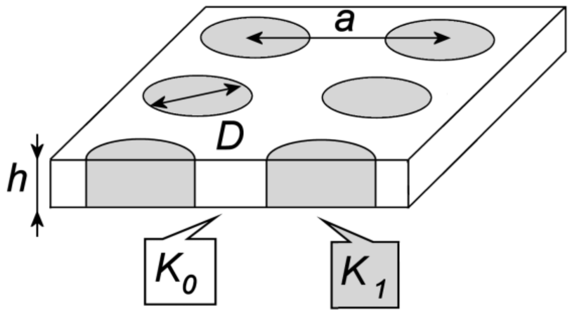

Fig. 1. Schematic drawing of the film with spatially modulated anisotropy parameter *K*.

The micromagnetic modeling was performed on the basis of numerical solution of the Landau-Lifshitz equation (LLE) for the magnetization of the sample using OOMMF package. The geometry of the simulated system and its material parameters are chosen corresponding to [1] and is the following: h = 7.5 nm, a = 200 nm, D = 100 nm (see Fig. 1), the saturation magnetization is 2×10^6 A/m, the exchange stiffness is 0.25×10^{-12} J/m, the initial anisotropy constant $K_0 = 3.65 \times 10^4$ J/m^3, the anisotropy constant of the modified area $K_1 = 2.38 \times 10^4$ J/m^3. The dissipation parameter of the LLE is 0.01. In numerical simulations we calculated the dynamics of the magnetization in the system under microwave magnetic field excitation [4]. As a result we obtained the spectra and spatial distributions of the oscillation amplitude

$$\boldsymbol{m} = (m_x^2 + m_y^2 + m_z^2)^{1/2}.$$

Initially the system was uniformly magnetized in an external magnetic field. Then the skyrmion states were formed under reversed magnetic field. Due to the difference in anisotropy the cylindrical regions and the rest film have the opposite directions of magnetization Fig. 2(a). The FMR spectrum and spatial distributions corresponding to the resonance oscillations are presented in Fig. 2.

The resonance peaks can be described as follows. First peak 1 is the mixture of main quasi-uniform resonance of internal skyrmion area and circular spin wave propagated near external boundary of domain wall. The second peak 2 is the mixture of domain wall resonance and spin wave propagated near internal boundary of skyrmion. The peak 3 is the second-order resonance of skyrmion area. The peak 4 is the resonance of internal region with circular spin wave. The peak 5 is the main resonance of quasi-uniform precession in perforated film. The peak 6 is mainly the second-order spin-wave resonance in perforated film.

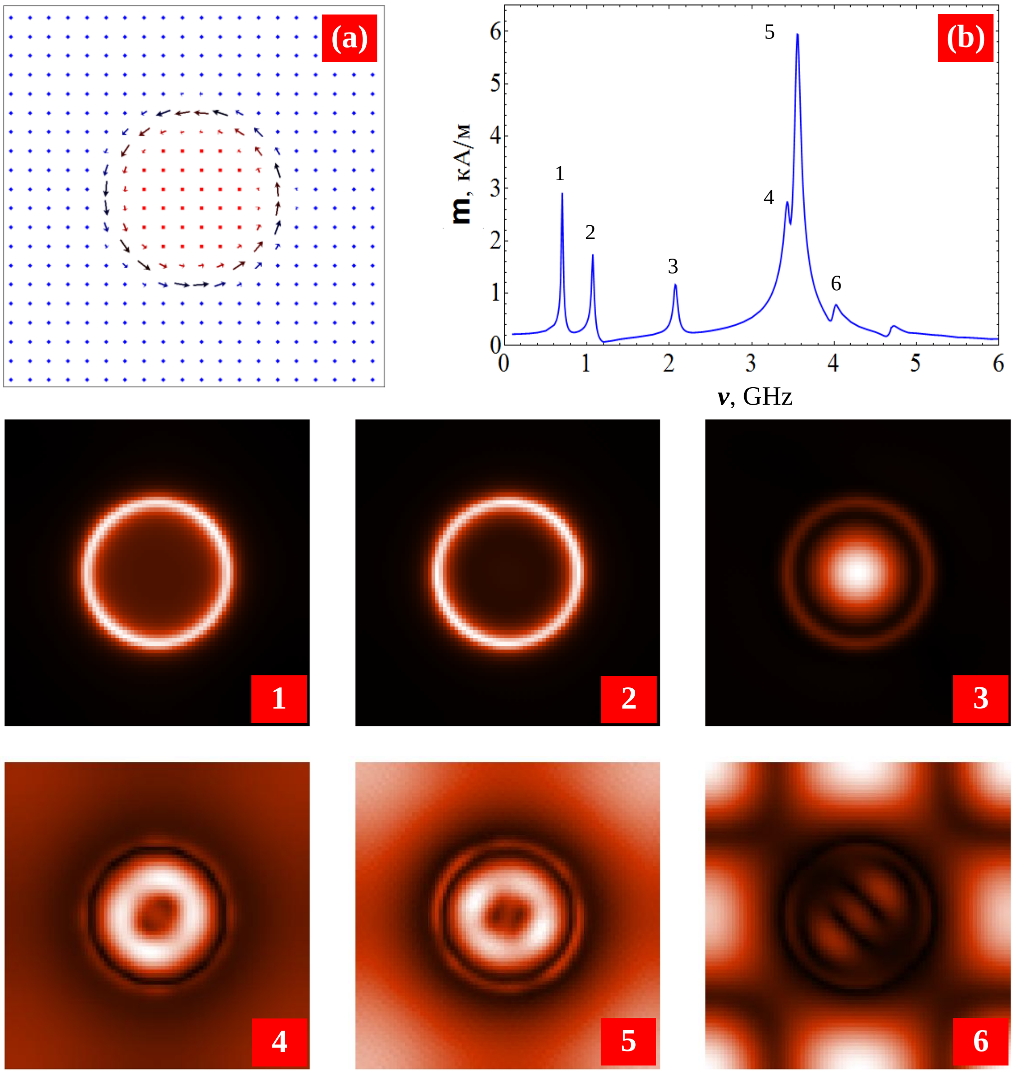

Fig. 2. (a) The magnetization distribution of sample area with magnetic skyrmion. The magnetization of central region is directed upward, while in periphery area downward. (b) The spectrum of magnetization oscillations. The spatial distributions of amplitude 1-6 correspond to the spectrum peaks 1-6.

Additionally, the FMR in the skyrmions induced in Co/Pt film by local field of magnetic MRFM probe is also discussed.

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Magnon spectrum in magnetic materials with skyrmion superlattice

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It has been experimentally established that vortex structures can be formed in thin films of magnetic materials under certain conditions. These structures are called skyrmions, whose properties have generated much interest both in terms of their basic physics as well as the possibility of technological applications.[1] [2]

If only the Heisenberg exchange between the spins is considered then the skyrmion configuration is higher in energy and thus metastable. However this case of Belavin-Polyakov skyrmion allows the analytic theoretical treatment, what concerns the form of the spectrum [3] and the role of the interaction between magnons [4].

Single skyrmion configuration becomes energetically favorable in presence of Dzyaloshinskii-Moriya interaction and external field. The extensive analysis of the magnon spectrum in this case was done in [4]. Our study of magnon spectrum generalizes the latter work by considering the hexagonal skyrmion lattice, which delivers the minimum classical energy in a range of parameters [5].

We approximate the hexagonal lattice by overlapping discs centered at the lattice sites. Each disc contains one skyrmion at its center. The period of this superlattice is found by minimization of the classical energy density. The discrete spectrum of magnons and their wave functions are found for individual discs. We show that two magnon bands lie below the usual continuum spectra and can be evaluated in the tight-binding model. These two low-energy bands are nearly flat due to small overlap of the corresponding wave-functions on the discs.

The quantum 1/s corrections to classical energy are numerically calculated which lowers the ground state energy and slightly redefines the period of SkX. It can be shown that the classical energy of SkX phase is higher than that of conical spiral state. Our calculation of quantum corrections to the energy indicates a wider region in parameter space, where the SkX is favorable.

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Session 10. Hall effect in chiral magnetic structures.

Chairman: Sergey V. Demishev

Fermi Surface Evolution and Quantum Criticality in $Mn_{1-x}Fe_xSi$

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Different scenarios of non-Fermi liquid behavior in strongly correlated electron systems may be resolved by a study of ordinary Hall effect in quantum critical (QC) regime [1-3]. For the system with localized magnetic moments a collapse of the Fermi surface should occur exactly at the QC point that can result in an abrupt change of the Hall constant at zero temperatures [2]. In contrast, the spin density wave model of quantum criticality in itinerant magnets provides no evidence of the Lifshitz transition at QC point [3].

Here we report the study of Hall effect in $Mn_{1-x}Fe_xSi$ (x<0.3) single crystals carried out in magnetic fields below 8 T at temperatures 2-60 K. Separating between ordinary and anomalous contributions to Hall effect in the paramagnetic phase of $Mn_{1-x}Fe_xSi$ allows to discover a sign inversion of normal Hall coefficient, which is definitely associated with the hidden QC point $x^*\sim 0.11$. We show that the increase of Fe content results in effective hole doping. This observation allows us to make some verifiable predictions in the field of fermiology, magnetic interactions, and QC phenomena in this QC system. The discovered redistribution between electron and hole regions of Fermi surface is considered as a main factor, which tunes the QC regime in $Mn_{1-x}Fe_xSi$ by modulating the Ruderman-Kittel-Kasuya-Yosida exchange interaction between the localized magnetic moments of Mn ions.

This work was supported by the RAS Programmes "Electron spin resonance, spin-dependent electronic effects and spin technologies" and "Electron correlations in strongly interacting systems".

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

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Spiral magnets $Mn_{1-x}Fe_xSi$ are characterised by the presence of unusual magnetic phases, which are intermediate between common paramagnetic phase (PM) and spiral magnet (SM) phase with the long-range magnetic order [1-4]. The intermediate magnetic (IM) phase can be considered as a magnetic analog of the blue fog phases in liquid crystals [5-7] or it can be referred as spin liquid state by the straightforward analogy from general physics, where the PM phase, SM phase with long-range order (LRO) and IM phase may be considered as magnetic replicas of the common gas, solid and liquid phases [5].

Nevertheless, sometimes the aforementioned description of the IM phases is disputed, and these specific magnetic states are treated as regions of pronounced magnetic fluctuations in the magnetic phase diagram [7]. In any case these specific phases are of magnetic nature and thus may be affected by external magnetic field. However, the influence of magnetic field on the phases with IM order has not been studied systematically so far. At the same time, an analogy with liquid crystals suggests that the external field may noticeably change the corresponding phase diagram [8].

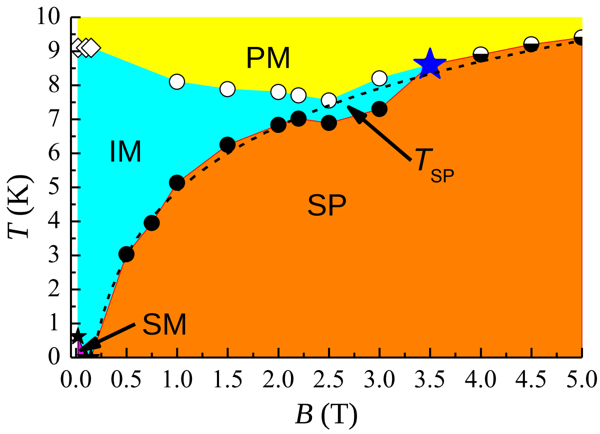

Fig.1 Magnetic phase *B-T* diagram for $Mn_{1-x}Fe_xSi$ with $x = 0.11$.

We have used a combination of two methods to probe the magnetic phase B-T diagram of the $Mn_{1-x}Fe_xSi$ single crystal in the proximity of the hidden quantum critical point $x^* \sim 0.12$. The first method consists of a comparative study of the temperature dependence of magnetic susceptibility $\chi(T)$ and related evolution of the neutron diffraction pattern [2] at the temperatures down to 0.4 K. The second method is based on analysis of the magnetoresistance data for 2-60K temperature range in magnetic fields up to 5 T [9].

It was found that in low magnetic fields B<0.15 T the IM phase with short-range magnetic order exists in a wide temperature range $0.62<T<9.1$ K (see Fig.1). It was discovered that the increasing of the magnetic field leads to the suppression of the transition between IM and SM phases at $T\leq 1$ K. Above that, the external magnetic field induces a boundary between intermediate and spin-polarized (SP) phases. The analysis of the results shows that the IM→SP transition temperature logarithmically increases with the magnetic field $T_{SP} \sim \log(B)$. As the result, there is a special point on magnetic phase diagram for T~8.5 K and B~3.5 T (star on Fig.1), which can be treated as a triple point in case of magnetic properties of $Mn_{1-x}Fe_xSi$ to be described by spin-polaron model [9,10], or critical point for ferromagnet with weak Dzyaloshinskii-Moriya interaction scenario.

The work was supported by RAS Programme «Strongly correlated electrons» and SAS projects VEGA 2/0106/13, APVV-14-0605 and CFNT MVEP.

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Session 11. Thin films and surface effects in cubic ferromagnets without center of symmetry.

Chairman: Dr. Sergey V. Demishev

Chiral Magnetic States in MnSi thin films

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A number of recent calculations and experiments have identified that strain and finite size effects are important contributions that influence the stability of the magnetic textures in MnSi thin films. Both of these effects play an important role in MnSi films grown on Si substrates and have an important influence on the magnetic phase diagram. However, there continues to exist controversy over the interpretation of the phase diagram. With insights from ferromagnetic resonance, magnetometry, Hall effect and polarized neutron reflectometry in out-of-plane fields, a consistent picture emerges with the cone phase as the sole equilibrium phase below the saturation field. Standing helimagnon waves are observed and represent the spin excitations from this ground state.

I will address recent controversy about the phase diagram in-plane magnetic fields [1-2]. We have explored the magnetic textures in three dimensions with the combination of PNR and small angle neutron scattering (SANS) measurements. While surface twists drive the skrymions into the film center, SANS demonstrates a large degree of disorder within the plane of the film.

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Electronic Transport in MnSi Thin Films and Nanostructures

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During the recent years, topology of spin structures has become an emergent topic in condensed matter physics. In this context, skyrmions are nano-scale spin vortices with fascinating physical properties, in particular the enhanced stability due to their non-zero topological winding number resulting in a topologically protected state. Together with their efficient coupling to the conduction electrons skyrmions could have a high potential for future data storage techniques.

The B20 helimagnets have been established as prime materials to study the physics of such skyrmionic phases [1]. The compound MnSi was the first example, where the formation of skyrmions could be observed in the solids state, which afterwards resulted in the discovery of a multitude of skyrmionic materials [2]. Bulk MnSi undergoes a magnetic transition into a helical phase below T_N = 29 K in zero magnetic field, which switches into a conical state upon increase of the field to 0.1 T. Furthermore the existence of skyrmions in the so-called A-phase has been established in the temperature range ~28–29 K and fields between 0.1 and 0.2 T [1].

For MnSi bulk material, thestudy of the properties regarding the skyrmion objects has been comprehensively done. This brings up the question whether in MnSi thin films and/or nanostructures the skyrmionic phase is present similarly as in bulk material. Even though theory predicts an enhanced stability of skyrmions due to uniaxial anisotropy [3], experimental studies on the detection of skyrmions in thin films have as yet been inconclusive. Implicitly, it is assumed that signatures in the magnetotransport and magnetization imply skyrmionic phases, although a topological Hall effect as unique signature of the A-phase in bulk MnSi [4] has never been reliably observed.

In this situation, we have set out to reinvestigate the (magneto-)resistivity and Hall effect in MnSi thin films. Samples of different thicknesses were grown by molecular beam epitaxy and characterized regarding their physical properties. Afterwards nanostructures of various sizes in Hall geometry were lithographically produced to determine the intrinsic transport properties with means of Hall and resistivity experiments. We compare bulk, thin film and nanostructure data and discuss our results in consideration of electronic correlations and structural as well as morphologic characterization of the samples.

We gratefully acknowledge support by the Braunschweig International Graduate School of Metrology B-IGSM and the DFG Research Training Group GrK1952/1 "Metrology for Complex Nanosystems".

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Time-dependent entanglement within a framework of Dzyaloshinskii-Moriya interaction effect

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The promise of quantum computers to solve classically non-computable problems has generated the great excitement and much research activity in different areas of physics, mathematics and engineering. However, for realization of this technology it is necessary to find suitable system for quantum bits (qubits) and meet challenges related with instability of quantum states. Solid-state spin-based systems are very attractive candidates for implementation of quantum bits due to the fact that there are well scalable. Also these systems can be fabricated by the methods of modern microelectronics, and advanced spin-resonance techniques are well-suited for the efficient quantum state manipulation.[1]

Furthermore, for effective using of quantum computer it is necessary to sustain the quantum entanglement between qubits during a long period of time, which is very important challenge. We think that Dzyaloshinskii-Moriya interaction effect may be a key to solving this problem.

In this publication we present results of research of time-dependent quantum entanglement within a framework of Dzyaloshinskii-Moriya interaction effect. We choose spin structure of cobalt dimer on aurum surface as a system. Research conducted using general spin Hamiltonian[2] and Landau-Lifshitz-Gilbert equation[3]. Also influence of Dzyaloshinskii-Moriya interaction effect on time-dependent quantum entanglement within different quantum gates (e.g. CNOT and SWAP) is considered.

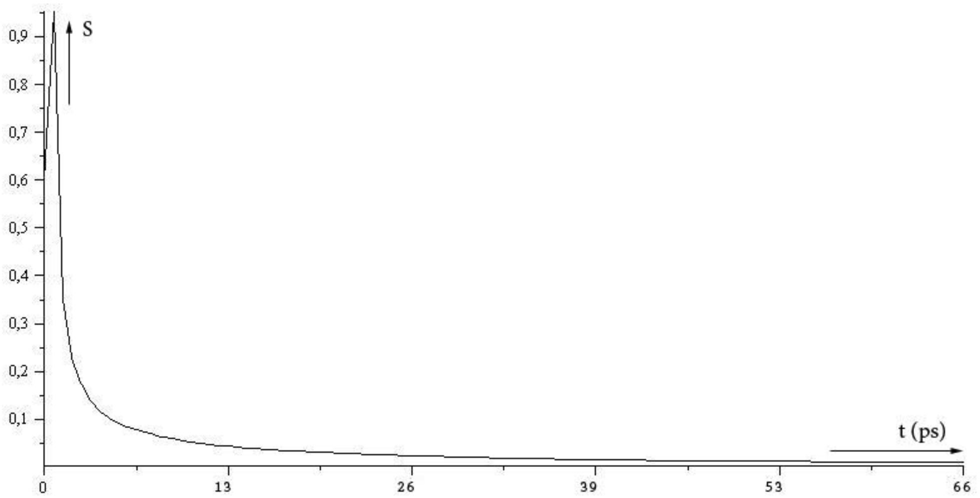

FIG. 1: Time evolution of Shannon entropy S of Co_2 on aurum surface without pulse and gates.

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Session 12. Antiferromagnets and multiferroics.

Chairman: Dr. Isabelle Mirebeau

Spin-orbit effects in non-collinear magnetism

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The spin-orbit interaction can induce not only canting of neighboring magnetic moments but also non-collinear intra-atomic magnetism in transition metals, lanthanides and actinides [1]; both phenomena will be discussed in this report. Novel experimental and theoretical techniques for determination of the sign of the Dzyaloshinskii-Moriya interaction (DMI) have been suggested in [2] and then realized in [3] for iron borate crystal $FeBO_3$. Here recent developments of these techniques will be presented and applied to several 3*d* transition metal carbonates with the DMI ($MnCO_3$, $CoCO_3$, $NiCO_3$ single crystals). The sign of the interaction is encoded in the phase of magnetic x-ray diffraction amplitude, observed through interference with resonant quadrupole scattering in the pre-K-edge region of the transition metals. Rotating the external magnetic field we can order and rotate the weak ferromagnetic moment and change this way the phase of magnetic x-ray diffraction amplitude. Experimental data have been supported by *ab-initio* simulations taking into account spin-orbit interactions [4]. It is revealed that the DMI sign in $MnCO_3$ coincides with that one in $FeBO_3$, whereas $CoCO_3$ and $NiCO_3$ demonstrate the opposite sign.

Strongly non-collinear intra-atomic magnetism has been found by *ab-initio* simulations in RhGe crystal with noncentrosymmetric MnSi-type structure. Experimentally, RhGe is weakly ferromagnetic below 140 K and superconducting below 4.3 K [5]. The Quantum Espresso calculations (LDA+U+SO) suggest that the observed weak ferromagnetism emerges as a byproduct of the pronounced toroidal-like spin polarization with magnetic quadrupole and toroidal moments located at Rh and Ge sites.

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Magnetic Structure and Excitation in Multiferroic Hexaferrites

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The discovery of magnetoelectric (ME) effects caused by a cycloidal spin order has initiated an intense research on new class of ME materials [1]. Among them one interesting class of materials is the hexaferrites such as Y-type ($A_2Me_2Fe_{12}O_{22}$: *Me*=transition metal) , M-type ($AFe_{12}O_{19}$: *A*=Pb, Ca, Sr, Ba, etc.), where types of elementary blocks and their stacking order are different [2]. These materials are being extensively investigated because they exhibit spin-driven ferroelectricity associated with non-collinear magnetic structures in relatively low magnetic field and high temperature region [3,4].

The Y-type hexaferrite $BaSrCo_2Fe_{11}AlO_{22}$ (BSCoFAO) was recently reported to exhibit spin-driven ferroelectricity and electric-field induced magnetization switching at room temperature [5]. At the same time the electric-field-active magnetic excitations, which is referred to as electromagnon can be expected in this Y-type hexaferrite, similar to the electromagnon in another Y-type hexaferrite $Ba_2Mg_2Fe_{12}O_{22}$ (BMFO) [6] .

In this presentation we report on the neutron diffraction and inelastic scattering experiment to determine the magnetic ordering and magnetic excitation in the room temperature multiferroic hexaferrite material BSCoFAO. The results will be discussed and compared with those of BMFO[7,8].

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Chirality evolution in RMn_2O_5

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Magnetic multiferroics (multiferroics, where magnetic order induces electric polarization) now are the subject of widespread investigations. Being now one of the most interesting challenges in the physics of strongly correlated systems, magnetic multiferroicity is promising for potential application in functional devices. Multiferroic family RMn_2O_5 (R – rare-earth element) demonstrates, probably, the most interesting and close interrelations between magnetism and ferroelectricity. The intensive investigations of the family are in progress during last years in order to elucidate the microscopic mechanisms leading to such remarkable magneto-electric properties. Notwithstanding on the great amount of the experimental and theoretical works devoted to RMn_2O_5, see e.g. [1, 2] and references therein, the mechanisms of ferroelectricity in this family still are not obvious.

Two different theoretical approaches are actual for the considerations of the basic mechanism, ensuring spin-driven ferroelectricity in RMn_2O_5. In the exchange striction model the electrical polarization arises due to symmetric exchange interaction [1, 2]. In this case the electrical polarization is proportional to the scalar product of adjacent spins $\boldsymbol{P}_e \sim[\boldsymbol{S}_i\cdot\boldsymbol{S}_j]$. Another model considers the antisymmetric Dzyaloshinsky-Moria interaction (DMI) as the origin of the polarization. In this case polarization is proportional to the vector product of adjacent spins $\boldsymbol{P}_e \sim[\boldsymbol{S}_i\times\boldsymbol{S}_j]$ [3, 4]. The consideration of antisymmetric exchange in the helically ordered spin system leads to the possibility of small displacements of O^{2-} ions, which enhance the DMI exchange interaction. The chirality of helical spin order specifies the direction of the ligand O^{2-} ions shifts and for helices with one chirality all ligands shift in the same direction, asserting electric polarization, which is perpendicular to the helix propagation.

In this report, we concentrated on the chirality investigations in manganites $TbMn_2O_5$, $NdMn_2O_5$. The studies were performed on the single crystals $TbMn_2O_5$ and $NdMn_2O_5$ with the use of different methods of polarized neutrons scattering: polarized neutron diffraction, XYZ-polarization analysis, spherical neutron polarization (SNP).

There are three magnetically ordered phases in $TbMn_2O_5$ below $T_N \approx 43$ K. First one, "high temperature incommensurate" phase for $T_C<T<T_N$ and ferroelectric phase corresponding to this magnetic phase considered to be "weak ferroelectric". Second one, commensurate phase for $T_L<T<T_C$, and ferroelectric phase emerging exactly in this temperature region, has much more polarization value and considered to be "ferroelectric". Third one, "low temperature incommensurate" phase for $T<T_L$ is also "weak ferroelectric".

We observed the difference in the population of domains with "right" and "left" spirals in $TbMn_2O_5$ by the polarized neutron scattering diffraction, by measuring the intensity dependence of the polarization direction. This difference has approximately the equal value for $n_r - n_l \approx 0.5$ for all magnetically ordered phases [5].

Our latest results, obtained by SNP [6], also indicate the difference in "right"-"left" population in $TbMn_2O_5$ in complete consistency with previous section. This fact confirms the efficiency of DMI in all magnetically ordered phases, since only this interaction can produce the difference in the domain population [7].

The results of our SNP experiments on $NdMn_2O_5$ single crystal also demonstrate chiral nature of the magnetic alignment. It should be emphasized that in this manganite the magnetic ordering takes place below T_N = 30 K [8]. But unlike $TbMn_2O_5$ which is chiral in all magnetic phases, $NdMn_2O_5$ is chiral only below 20 K. Recently it was established, that ferroelectricity in this compound (in single crystal) emerges at 20 K [9]. Thus it is natural to suppose the chiral magnetic alignment could be driving force for the ferroelectricity in both $TbMn_2O_5$ and $NdMn_2O_5$ manganites. Interestingly the temperature evolution of chiral scattering has difference in “cooling” and “heating” modes. But this different temperature behavior follows the temperature hysteresis of propagation vector rather than integrating intensity of magnetic scattering.

The application of external electric field leads to the change of the population of domains with “right” and “left” helices in both compounds. Investigations were made in “Field Cooled” modes (FC). In this way for $TbMn_2O_5$ with FC -3 kV/cm we could equalize population of “right” and “left” helices, then with FC +3 kV/cm we return chiral system of $TbMn_2O_5$ to the initial ZFC value. For $NdMn_2O_5$ application of external field FC ± 4 kV/cm was enough to increase/decrease difference in helices population by +13% / -25% from ZFC value.

Qualitative consideration of superexchange DMI interaction for RMn_2O_5 through ligand ion [10] permits to conclude about the possibility of Dzyaloshinsky vector ***D*** to lay in the direction close to ***c****** - situation which was determined from our studies.

Our results confirm the assumption, that the antisymmetric exchange interaction should be considered as the origin of spin driven ferroelectricity in RMn_2O_5. The symmetrical exchange mechanism is effective in commensurate phase, where it enhance electric polarization.

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Second harmonic generation in non-collinear magnetic system due to spin current: theory and experiment

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We report theoretical and experimental studies of the new mechanism of second harmonic generation (SHG) induced by spin current in a non-collinearly magnetized medium. Spin current is the flow of spin, which may be accompanied by the flow of electric charge. A special kind of spin current systems is a system where the pure spin current exists in equilibrium [1], when the charge flow is zero. Such a case can be realized in magnetic systems with non-collinear magnetization distribution. They attract attention due to new interesting properties induced by the simultaneous inversion and the time reversal symmetry broken in equilibrium in such systems. This leads to a number of new phenomena, such as the flexo-magnetoelectric effect predicted in non-collinearly magnetized media [2,3] and the second harmonic generation induced by the spin current [4]. Due to its high symmetry sensitivity, the SHG effect is considered as a sensitive tool for the spin current diagnostics. The mechanism of the second-order non-linear optical effect due to the pure spin current in the non-collinear magnetic system has not been considered till now. In this work we study the microscopic mechanisms of the second harmonic generation in such system. The magnetic-field induced SHG is investigated experimentally in a multilayer magnetic system that consists of the two interacting subsystems with the perpendicular (out-of-plane) and with the in-plane magnetic anisotropy.

Symmetry considerations show that in such a system there can be the SHG polarization P(2ω) contribution proportional to the equilibrium spin current described by the second-rank tensor S_{jk} and to the wave electric field **E** squared. Hence the SHG polarization P(2ω) is determined by a fifth-rank susceptibility tensor. The magnetic indices are intrinsically coupled to the coordinate indices here. Therefore the second-harmonic generation due to the spin current may be obtained only if the spin-orbit interaction is taken into account in addition to the exchange interaction. In our theoretical investigation, we use the hydrodynamic approach, which considers the delocalized (conduction) electrons of a medium as the source of its optical response. The Euler equation for the velocity of the electrons is accompanied by the mass and spin conversion laws. The quasistatic Maxwell equation is used to describe the induced electric field. The spin-orbit interaction is taken into account by considering the anomalous Hall effect and the inverse spin Hall effect which transforms the spin flow to the current flow. We calculate the second order polarization in the frame of the described model. It consisting of the non-adiabatic spin polarization of the conduction electrons which appears due to the oscillations of the electrons in the non-uniform magnetization forced by the electric field of the electromagnetic wave. This spin leads to the spin current at the SHG frequency that is converted to the electric current via the inverse spin Hall effect. This mechanism reveals a resonance at the conduction electron plasma frequency. We estimate the obtained effect for the parameters of Ni (nanostructured with a 10 nm scale of the magnetization change). The second order nonlinear susceptibility at the plasma frequency is ~10^{-9} esu. Thus, we theoretically show the possibility for the experimental observation of this effect.

The schematic view of the studied structure is shown in Figure 1. We use a multilayer ferromagnetic sample [Co (0.5nm) / Pt (1 nm)]x3 / Pt (3 nm) / Co (3 nm) grown by magnetron sputtering on silicon or fuzed quartz substrates. The sample consists of a subsystem with the perpendicular magnetic anisotropy (Co/Pt trilayer) and a subsystem with the in-plane anisotropy (3 nm - thick Co layer) separated by a 3 nm - thick Pt spacer. The subsystems weakly interact through such a spacer [5]. Therefore we may control the magnetization of each layer. If an external magnetic field is applied in the layers plane, the thick Co layer reverses its magnetization in a small field (tens of Oe), while the Co/Pt subsystem is splitted into domains in a higher field (hundreds of Oe) and is magnetized in the sample plane in a much greater field. In accordance with the symmetry analysis, the experiments are performed for the longitudinal magnetic field and for the p-in, p-out(SHG) combination of polarizations. In that case, the magnetization-induced SHG from individual layers is absent due to the symmetry restrictions. However we observe the SHG effect in such geometry in a weakly interacting system, which appears as a magnetic hysteresis in the SHG intensity as is shown in Figure 2. The width of the hysteresis loop corresponds to the magnetization reversal of the thick Co layer. Such effect is absent for a simple systems with a uniform Co (3 nm) film or for a [Co (0.5nm) / Pt (1 nm)]x3 multilayer. Thus the SHG dependencies attained for the structure with non-collinear magnetization is a manifestation of the spin-current induced SHG.

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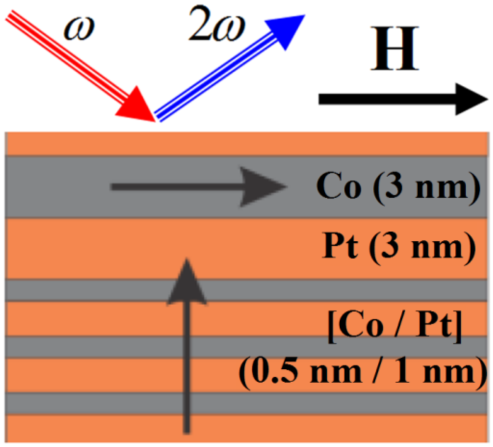

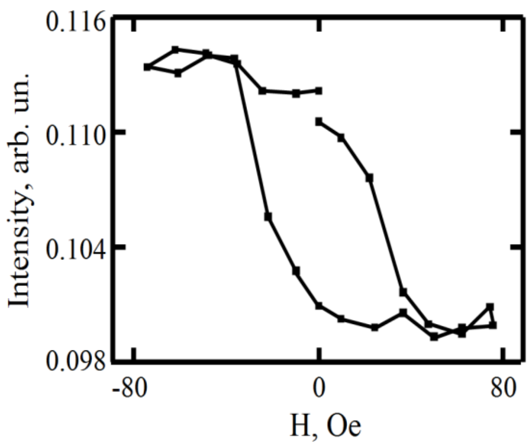

Figure 1. Schematic view of the sample and the geometry of the experiment.
Figure 2. Second harmonic intensity hysteresis for the -p-p combination of the pump and second harmonic signal polarizations.

Probing chirality with high energy synchrotron light

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Absolute structure determination using hard x-rays is considered as problematic because of the small resonant contributions for many chemical elements. Here we show that even small resonant contributions can be safely detected at high energy. This is due to the large number of the observable Bijvoet differences which are available, and that the signal increases with Q due to the form factors, so that absolute structure determination becomes possible.

The absolute structure has been determined for a crystal of MnSi with data collected using synchrotron radiation with E = 78.3 keV. At this energy, the resonant scattering contribution from MnSi is very small f'(Mn) = -0.0397, f''(Mn) = 0.0385, f'(Si) = -0.0197, f''(Si) = 0.0027). A comparison with the data collected at E = 18 keV (f'(Mn) = 0.2858, f''(Mn) = 0.6739, f'(Si) = 0.0653, f''(Si) = 0.0646) for the same crystal shows the correctness of the absolute structure measured at the high energy. Similar data collections have also been carried out for crystals with known absolute structures: Fe(0.7)Co(0.3)Si at E = 65.2 keV; in all the cases, the absolute structure was correctly determined by analyzing the statistical distribution of the chirality measure. Statistical descriptors of the refinements, Flack parameter, and the distribution of Parsons quotients are discussed for all presented experiments.

Session 13. Neutron scattering for non-collinear magnetism.

Chairman: Dr. Kazuhisa Kakurai

Bilayered crystal of *magnetic monopoles* and multiferroicity in spin ice

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In geometrically frustrated pyrochlore magnets, the magnetic interactions cannot be simultaneously satisfied, leading to short-range magnetic orders called spin ices or spin liquids. Spin ice support an extensively degenerate ground state and ensure the local conservation of magnetic fluxes. Such flux conservation can be described as Coulomb spin liquid by analogy with Maxwell's electromagnetism where excitations take the form of emergent *magnetic monopole*. It was found that under a field spin liquid Tb2Ti2O7 orders as a three dimensional arrangement of *magnetic monopole* and *antimonopole* double layers [1]. Recent theory shows that magnetoelectric coupling in pyrochlores is able to lift the degeneracy and to manipulate topological excitations [2]. As a result the electric dipolar interactions can be responsible for the emergence of the double-layer structure of *monopoles*.

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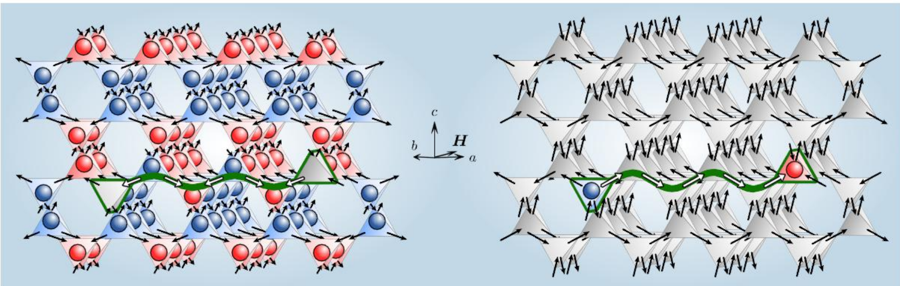

Fig. 1. Magnetic structures of Tb2Ti2O7 (left) and Ho2Ti2O7 (right) in [110] field.

Nonreciprocal neutron diffraction on helical magnets

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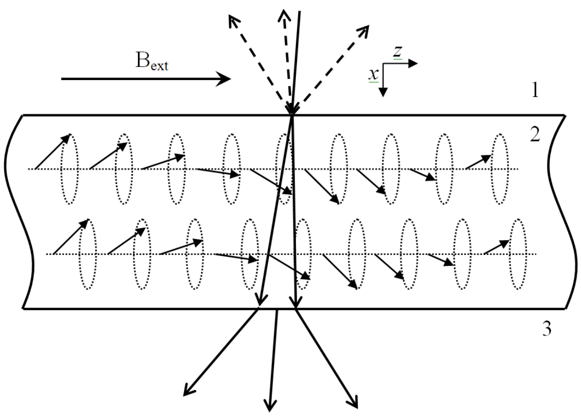
The magnetic properties of not center symmetric cubic magnets are under intensive study [1, 2]. Due to the antisymmetric Dzyaloshinskii–Moriya exchange interaction [3, 4], in such crystals, helical magnetization distribution is realized, in which the period of the magnetic superstructure substantially exceeds the interatomic distance. An additional weak anisotropic interaction fixes the direction of the helix [5]. On an application of an external magnetic field along the axis of the helix, the magnetic induction distribution becomes noncoplanar. According to the theoretical predictions [6–8] and the experiment [9], neutron scattering by systems with a noncoplanar distribution of the magnetic field is nonreciprocal. We calculate the magnitude of effects caused by the nonreciprocal neutron scattering on the small angle diffraction by crystals with a helical magnetization distribution.



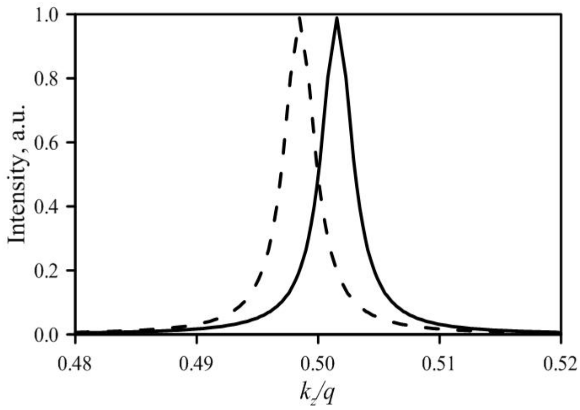


Fig.1. (a) The scheme of neutron diffraction on helical magnets; (b) Calculated nonreciprocal scattering in the diffraction $T_{-+}(\mathbf{B})$ (see text); solid and dashe lines correspond to opposite directions of the external magnetic field.

The Schrodinger equation for the neutron motion in a medium with a helical distribution of the magnetic field in dimensionless units ($\frac{2mV_0}{\hbar^2}=1$) has the form

$$-\Delta\hat{\psi}+\hat{\psi}+k_B^2\begin{pmatrix}\cos\theta & \sin\theta e^{-iqz}\\ \sin\theta e^{iqz} & -\cos\theta\end{pmatrix}\hat{\psi}=k_0^2\hat{\psi}\,, \qquad (1)$$

where m is the neutron mass, V_0 is the value of the nuclear potential, $\hat{\psi}$ is the spinor wave function of a neutron, $k_B^2=\frac{\mu_n B}{V_0}$ is the value of the interaction of the neutron magnetic moment μ_n with a magnetic field B in dimensionless units, θ is half the apex angle of the cone of the helix, k_0^2 is the energy of the incident beam in dimensionless units, and q is the reciprocal vector of the helix. The spectrum and the wave functions of neutrons described by Eq. (1) are well known [10, 11].

Let us consider the neutron transmission through and reflection from a medium of finite thickness L with a conical magnetization distribution (Fig. 1a). In order to find the reflection and transmission coefficients, it is necessary to find the wave functions satisfying the boundary conditions on interfaces 1–2 and 2–3. The full solution can be found in [12].

Let us consider the diffraction by the helix with a spin flip from the state "–" to the state "+" on the transmission. Let us change the direction of the magnetic field to the opposite one and use the rotation symmetry of the differential scattering cross section [6]. Namely, after inverting the magnetic field, we rotate the field around the z-axis by the angle π:

$$T_{-+}\left(-B_x,-B_y,-B_z\right)=T_{-+}\left(\hat{R}_{z,\pi}\left(-B_x,-B_y,-B_z\right)\right)=T_{-+}\left(B_x,B_y,-B_z\right). \tag{7}$$

In other words, to measure the nonreciprocity in a small angle diffraction by a helix, it suffices to change the direction of the external magnetic field, leaving the other projections of the helicoid field unchanged.

In the general case, diffraction by a lattice with a wavenumber q has a resonance for the diffraction peak of order "–1" if the projection $k_{0z} \approx q/2$. Correspondingly, one should also expect a resonance behavior for the peak $T_{-+}(\mathbf{B})$. The absolute value of the external magnetic field is 1 kOe. Depending on the direction of the field applied, the position of the diffraction peak changes. Let us show that a shift of the diffraction maximum is possible only in a noncoplanar system. Assume that an MnSi crystal with a plane helicoid distribution and an external field are two independent scatterers. A plane helicoid is noncollinear and admits processes with a spin flip. The external field is similar to a homogeneous magnetized mirror and, therefore, refraction in it depends on whether the neutron spin is directed along the field or against the field. As was shown in [6], nonreciprocal effects are observed only beyond the single-scattering Born approximation. For simplicity, let us consider the double-scattering process. Then, after diffraction by the helicoid with a flip from the state "–" to the state "+", the beam is also refracted in a uniform external magnetic field. It is clear that, in this case, the transmission intensity depends on the mutual orientation of the spin state "+" and the external magnetic field. Taking into account the resonant character of $T_{-+}(\mathbf{B})$ near $k_{0z} \approx q/2$, we obtain a shift of the resonance peak, linear in the magnetic field (Fig. 1b). The value of the shift is on the order of $0{,}01q \approx 3\times10^{-4}$ Å^{-1}.

In this work, we have presented the results of exact analytical calculation of the small angle neutron scattering by not center symmetric cubic magnets with a helical distribution of the magnetization. It has been shown that the shift in the external field of the small angle diffraction peak is observed. Also, it has been shown the shift is equal to the nonreciprocal scattering.

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Effect of Dzyaloshinski-Moriya interaction on spin-polarized neutron scattering.

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While the scattering theory allows to express the scattering cross section for an arbitrary distribution of scatterers, it is always advantageous to make use of correlations between different scattering centers, if they are known. In ferromagnets, the local magnetic moments, which scatter the neutrons, are not arbitrary, but their distribution is subject to the equations of micromagnetics.

In the case of an inhomogeneous material in a state, close to the magnetic saturation, the micromagnetic problem possesses a small parameter and can be solved to an arbitrary order [1] under a very general assumptions. The resulting squared Fourier components of the magnetization vector field, from which the small-angle neutron scattering (SANS) cross section can be directly computed, display a rich structure and are shown in Figure. This talk reports the solution of the micromagnetic problem in an inhomogeneous material with random Dzyaloshinskii-Moriya (DM) interaction and the consequences for the SANS cross sections in such a material [2].

It was predicted by A. Arrott that the DM interaction should arise in a very general setting of inhomogeneous magnets due to the local symmetry breaking. We show the criteria of pinpointing this emergent DM interaction using SANS [2].

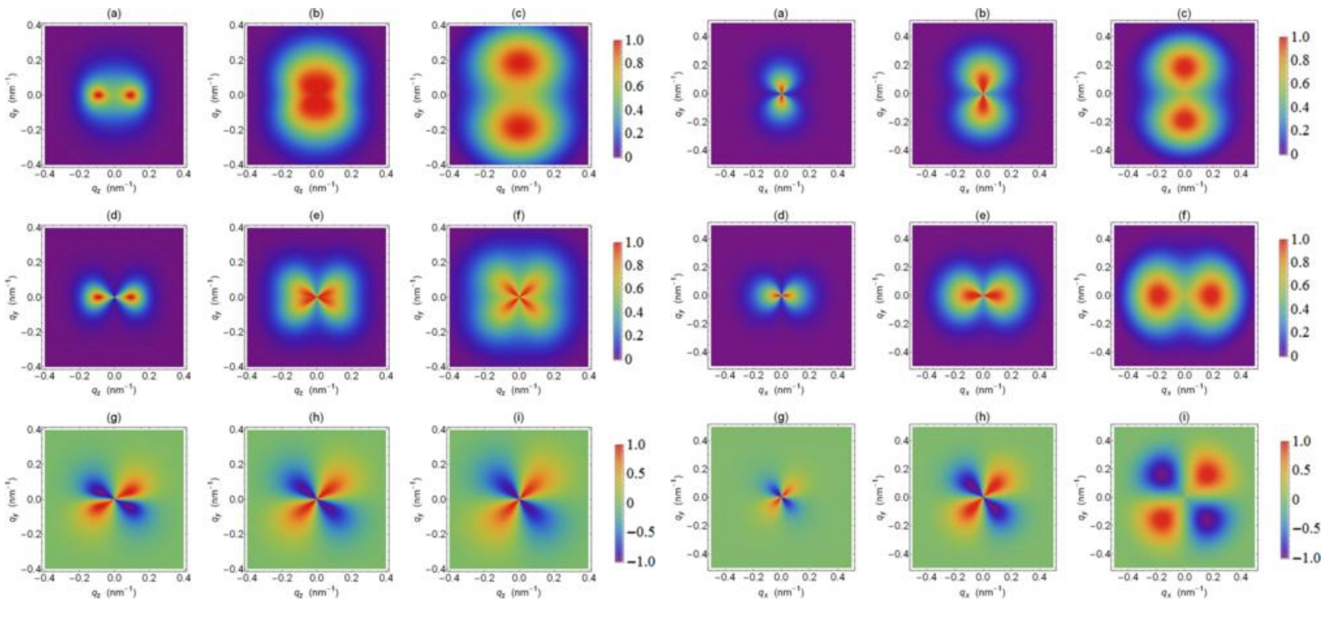

Figure. Averaged Fourier images of magnetization vector components in a randomly inhomogeneous bulk ferromagnet, relevant to computing the perpendicular $\boldsymbol{k} \perp \boldsymbol{H}$ (left) and parallel $\boldsymbol{k} \parallel \boldsymbol{H}$ (right) SANS cross sections [1, 2]. The rows on the left show field evolution of $|M_X|^2$, $|M_Y|^2$ and of the cross-term $-(M_Y M_Z + M_Y M_Z)$ at $q_X=0$, the rows on the right show the same for $|M_X|^2$, $|M_Y|^2$ and the cross-term $-(M_X M_Y + M_X M_Y)$ at $q_Z=0$.

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12.

Magnetism of layered triangular antimonates and tellurates with and without existence of structural and magnetic chiralities coupling

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Low-dimensional spin-frustrated systems frequently adopt noncollinear incommensurate spin arrangements to reduce the extent of their spin frustration. Dzyaloshinsky-Moriya interaction in the chiral-lattice ferromagnets (FM), in favor of a mutually canted spin arrangement, leads to the formation of chiral magnetic structures. Similarly, in the antiferromagnets (AFM) with a chiral lattice there are also unique magnetic structures characterized by chirality. The typical example is AFM with the triangular-lattice. The chirality of the magnetic structure in these compounds is always single handed and is related to the basic crystallographic chirality due to the asymmetric distribution of the exchange interactions. Since the chirality of the magnetic structure is closely related to spin helicity and is associated with the sign of electrical polarization, such materials with a chiral lattice are supposed to be carried forward to host distinctive magnetoelectric responses in comparison with centrosymmetric materials [1].

In the presented work, $MnSb_2O_6$ and $MnSnTeO_6$ oxides were studied by various physical techniques. Neutron powder diffraction (NPD) was the main research method. The layered crystal structure combined with the triangular geometry of the magnetic lattice of manganese makes these materials extremely promising for discovering new features of the formation of the quantum ground states of matter. Geometrical spin frustration arises when the spin exchanges between adjacent magnetic ions are AFM. Such spin states may remove inversion symmetry and hence induce ferroelectric polarization. Competing interactions in spin-frustrated systems often result in an unusual critical behavior near the transitions towards novel magnetic phases. Quite recently, $MnSb_2O_6$, a magnet with a chiral crystal structure (s.g. *P321*), was predicted to be multiferroic with unique ferroelectric switching mechanism [2]. We have discovered and synthesized a new centrosymmetric trigonal (s.g. *P-31m*) form of $MnSb_2O_6$ that differs from the known form $MnSb_2O_6$ (s.g. *P321*). Fig. 1. shows two crystal structures of $MnSb_2O_6$.

Also we have synthesized and investigated $MnSnTeO_6$ with a chiral crystal (and magnetic) structure as a certain analog of chiral $MnSb_2O_6$. This is strictly isoelectronic phases. Experimental low-temperature NPD patterns for all samples show additional reflections associated with neutron magnetic scattering AFM nature that appear at temperatures below T_N.

On the basis of mathematical processing of low-temperature neutron powder diffraction data the models of magnetic structure are constructed for both compounds. Spin ordering of centrosymmetric samples is described by the propagation vector k = (1/3, 1/3, 1/5), which describes a complex non-collinear, but commensurate magnetic structure. Spin ordering of non-centrosymmetric samples is described by the propagation vector k = (0, 0, 0.183), which describes simpler non-collinear, and already incommensurate spiral magnetic structure ordered along the direction of layers stacking (fig. 2).

Common features of spin ordering are presented and the reasons resulting in distinctions between them are analysed.

Magnetic susceptibility and specific heat data are well consistent with the neutron results.

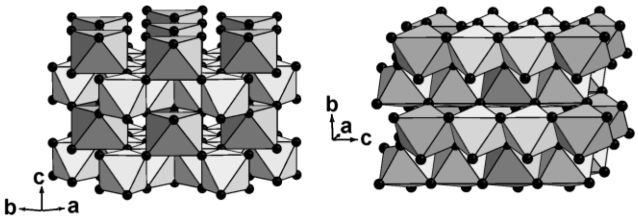

Fig. 1. Two crystal structures of $MnSb_2O_6$ in polyhedral presentation: new centrosymmetric trigonal form *P-31m* (left) and known non-centrosymmetric tetragonal form *P321* (right). Lighter octahedra, SbO_6; darker octahedra, MnO_6; black balls, oxygen anions. In the left structure, SbO_6 and MnO_6 octahedra are distributed in different layers. Octahedra populated with lower-valence cations (Mn) have no shared edges at all whereas those with higher-valence cations (Sb) share three edges each. In the right structure, the octahedra of both types are mixed ordered over all layers. Each metal-oxygen octahedron shares two edges with other octahedra, and higher-valence cations (Sb) have only one common edge.

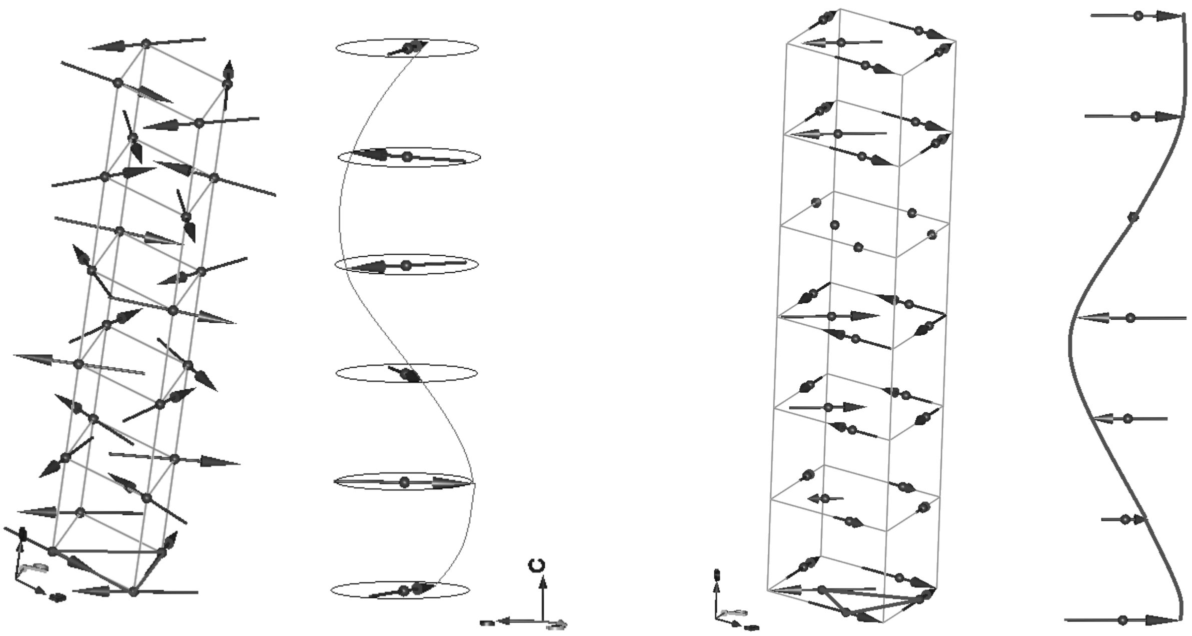

Fig. 2. Two magnetic structures (three-dimensional and projection) of centrosymmetric $MnSb_2O_6$ (left) and non-centrosymmetric $MnSnTeO_6$ (right).

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POSTER SESSION

$Mn_{1-x}Fe_xSi$ as a Liquid Crystal.

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Striking similarity between spiral magnets and liquid crystals was pointed out by Tewari et al. [1]. It was assumed that the spin-liquid phase developing as a result of long-range magnetic order suppression may be treated as an analogue of the blue fog phase [2]. In the present work, taking $Mn_{1-x}Fe_xSi$ solid solutions as a model object, we will show that there are more parallels between liquid crystals and spiral magnets may exist. First of all, it is possible to notice the practical coincidence of the X-rays and neutrons scattering patterns in the magnetic phases with an intermediate magnetic order in $Mn_{1-x}Fe_xSi$ [2] and in the nematic and smectic phases [3]. Moreover, phase transitions preceding the formation of the phase with long-range magnetic order in $Mn_{1-x}Fe_xSi$ [2] may be interpreted as a sequence of phase transformations isotropic liquid to nematic and nematic to smectic. These transitions may be accounted in the framework of the generalization of the phase diagram model [4,5] on the anisotropic case, corresponding to progressive 1D$\rightarrow$2D$\rightarrow$3D ordering with lowering temperature. In this ansatz, the paramagnetic phase of become an analogue of an isotropic liquid rather than chiral gas as it was suggested earlier [1]. Recent investigations of the paramagnetic phase in $Mn_{1-x}Fe_xSi$ [6,7] clearly demonstrate the presence of spin correlations on the nanoscale below T<60 K caused by spin-polaron effects. We argue that just spin polarons in the paramagnetic phase make liquid crystals analogy working giving rise to spin nematic and spin smectic effects.

This work was supported by programmes of Russian Academy of Sciences “Electron spin resonance, spin-dependent electronic effects and spin technologies”, “Electron correlations in strongly interacting systems” and by RFBR grant 17-02-00135.

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Magnetic phase diagram of $Y_{1-x}Tb_xMn_6Sn_6$ (x = 0, 0.175, 0.2, 0.225, 0.25) compounds.

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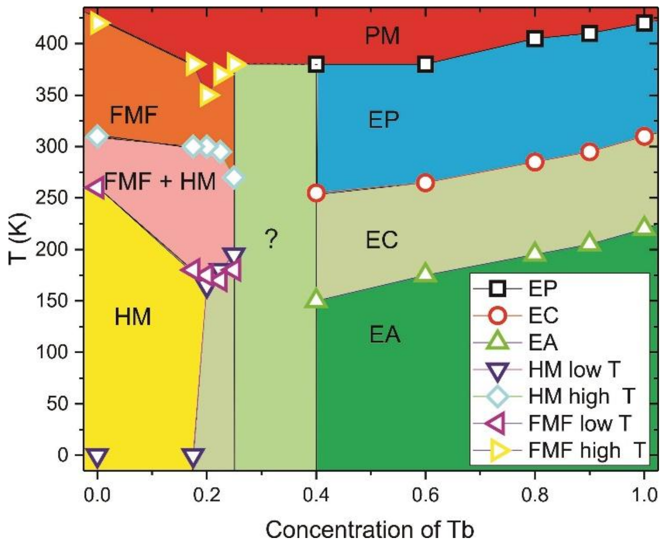
Over the last years, researchers have focused their attention on compounds, which possess a natural magnetic layered structure. A number of studies have been devoted to the RMn_6Sn_6 compounds with layered crystal structure, where R = rare earth ion [1-5]. The $Y_{1-x}Tb_xMn_6Sn_6$ compounds (x = 0, 0.175, 0.2, 0.225, 0.25) were studied by small angle neutron scattering (SANS) and paramagnetic neutron spin echo. The YMn_6Sn_6 compound is found to be a helimagnet in the whole temperature range below T_N = 310 K. Close to T_N an additional peak of a Lorenz shape was observed at Q = 0. The peak is thought to have originated from the ferromagnetic fluctuations of the magnetic Mn moment in the ab-plane of the hexagonal crystal structure. Compounds, in which Y is replaced by Tb, change their magnetic order with the increase of temperature: from easy cone ferromagnetic phase at low T through the helicoidal phase to the ferromagnetic fluctuation close to T_N. Temperature-concentration phase diagram of $Y_{1-x}Tb_xMn_6Sn_6$ is built on the basis of the obtained data.



The Magnetic phase diagram of $Y_{1-x}Tb_xMn_6Sn_6$ compounds. Data for concentrations higher than x = 0.25 are taken from [3].

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Magnetic Field Induced Griffiths Phase in $Mn_{1-x}Fe_xSi$ Solid Solutions

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In the present work, we report the results of systematic study of magnetic properties of $Mn_{1-x}Fe_xSi$ solid solutions (iron concentration x = 0.054, 0.11 and 0.19) in the high magnetic field (up to 50 T). Pulsed field magnetization measurements were performed in KU Leuven, Belgium [1].

Our MPMS-5 (Quantum Design) measurements show that magnetization $M(B, T)$ of $Mn_{1-x}Fe_xSi$ does not saturate in the field up to $B \sim 5.5$ T. In our previous work [2] supposed that $M(B)$ may have two contributions: the saturating one provided by spin-polaron subsystem and some additional linear term $M \sim B$. To understand the real magnetization structure it is instructive to perform high field magnetization measurements.

It is found that magnetization of $Mn_{1-x}Fe_xSi$ does not saturate even in the high magnetic field up to 50 T [3]. Analysis of the experimental data shows that in the $B > \sim 10$ T and in the paramagnetic phase magnetization $M(B)$ increases according to the power law $M(B) \sim B^{\alpha}$ with α = 0.3-0.5 (fig. 1).

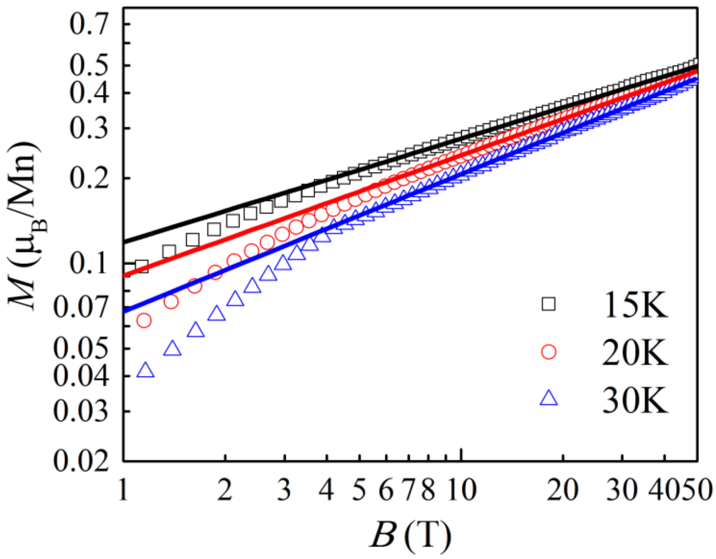

Fig. 1. Experimental $M(B, T)$ data for the sample with iron concentration x=0.11 (points) and high-field power law fits (lines).

Power law observed in $M(B)$ dependence is very unusual and may be explained qualitatively by the realization of the quantum critical Griffiths phase in the high field region [3,4]. At the same time, low field analysis shows that low field magnetization is linear $M(B \rightarrow 0) \sim B$. We suggest that high field induced Griffiths phase is formed by spin polarons [5], which may play a role of intrinsic nanoscale magnetic inhomogeneities.

This work was supported by programmes of Russian Academy of Sciences "Electron spin resonance, spin-dependent electron effects and spin technologies" and "Electron correlations in strongly interacting systems".

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Magnetic and magnetoelectric properties in a chiral polar magnet Ni_2InSbO_6

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Magnetoelectric (ME) multiferroics, in which ferroelectric polarization and magnetic orders are strongly combined, have been attracting much attentions [1]. Recently, Ni_3TeO_6 has been intensively studied because of the colossal ME response upon spin-flop transition [2]. Ni_3TeO_6 crystallizes in a corundum-related trigonal lattice with a chiral polar space group *R*3. Moreover, this structure is robust against some substitution of cation site. Ni_2InSbO_6 is obtained as a result of substitution of In^{3+}-Sb^{5+} for Ni^{2+}-Te^{6+} in Ni_3TeO_6. This compound shows long-period helimagnetism with the propagation vector of helix along the *b** axis below 76 K according to a previous neutron study [3]. However, the magnetic structure analysis was performed only on polycrystals and the ME effect has not been revealed so far in this material.

In this presentation, we report magnetic and ME properties in single crystals of Ni_2InSbO_6. Single crystals of Ni_2InSbO_6 were successfully grown by chemical vapor transport method (Fig. 1). We measured the magnetization, dielectric constant, and electric polarization, and found a strong coupling between magnetism and electric polarization in this material. By using a pulsed magnet, it has been revealed that Ni_2InSbO_6 shows a metamagnetic phase transition in a high magnetic field and electric polarization is modified through this transition. In addition, dielectric permittivity is changed drastically with increasing magnetic fields.

The results can be summarized in magnetic field – temperature phase diagrams as shown in Fig. 2.

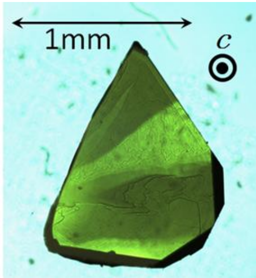

Fig. 1: Optical transmission polar- izing microscope image of a single crystal of .Ni_2InSbO_6. The contrasts are ascribed to domains with differ- ent chiralities.

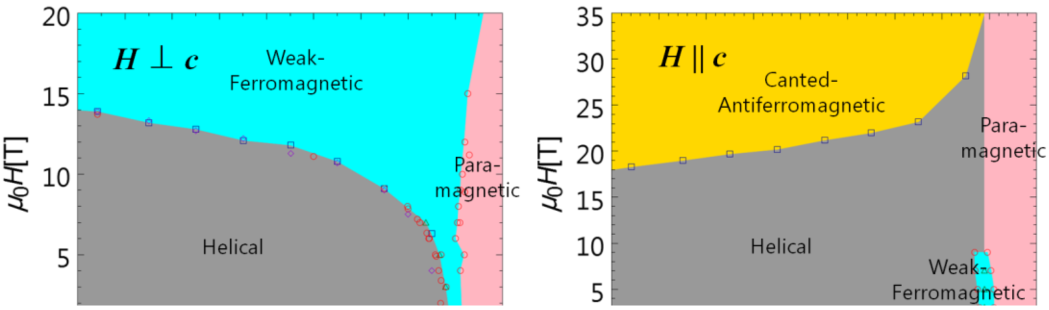

Fig. 2: Magnetic phase diagrams of Ni_2InSbO_6

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Stereographic projection approach to skyrmionic spin structures.

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There is a renewed interest in different topological defects in magnets in recent years [1]. One of the topics of active investigation is skyrmions in two-dimensional ferromagnetic films [2].

In the seminal paper [3] by Belavin and Polyakov (BP) the existence of topological solitons in O(3) sigma-model has been discussed. Remarkably, the energy of the multi-skyrmion state in this model does not depend on the configuration of individual skyrmions, i.e. on their radii and distance between them. In other words, there is no interaction between skyrmions.

We study the extension of this non-linear O(3) sigma-model at T=0, by adding Dzyaloshinskii-Moriya interaction (DMI) and external magnetic field. The analysis is done with stereographic projection approach, by describing the magnetization vector field as to complex-valued function. We write a variational equation for the energy. First we find a numerical solution for individual skyrmion, which is of BP type with additional profile factor appearing due to DMI and the field. Next we discuss many-skyrmion configurations as simple sums of stereographic projections of single skyrmions. Such simple sum corresponded to the exact solution in BP case and we expect that this sum is nearly exact in our case due to exponential decay of the profile factor.

Proceeding this way, we calculate the interaction between two and three single skyrmions. We find that the triple interaction is sizable as compared to pairwise soliton interaction. Therefore the system is not reduced to an analog of Coulomb gas with screened repulsion. Our analysis provides an alternative way of calculation of the classical energy density in skyrmion crystals.

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Neutron scattering cross section on spin-waves in full polarized state in helimagnets

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We have developed the analytical approach to the small-angle neutron scattering on spin waves in Dzyaloshinskii-Moriya helimagnets, formed in the cubic crystals without the center of inversion (the spatial $P2_13$ group). The spin waves dispersion of helimagnets, being in the state fully polarized by the magnetic field, has the following form:

$$E_q = A(\vec{q} - \vec{k}_s)^2 + (H - H_{C2}) = A\vec{Q}^2 + \Delta\,, \qquad (1)$$

where A is spin wave stiffness, $\vec{k}_s$ is a spiral vector of helimagnets. The cross-section of neutron scattering on the two-dimensional map of the scattering angles (θ_x, θ_y) is shown to be the two circles of the radius θ_C. The centers of these circles coincide with the spiral Bragg angle $\pm\theta_S$, which is oriented along the applied magnetic field of **H**. The radius of the circles is directly related to the spin wave stiffness and it depends on the applied magnetic field. We show that the scattering cross-section depends on the neutron polarization that demonstrates the chiral character of spin waves in Dzyaloshinskii-Moriya helimagnets even in full-polarized phase.

The components of the scattering vector q in the case of small-angle scattering can be represented in the following form:

$$\begin{cases} q_x = k_i\theta_x, \\ q_y = k_i\theta_y, \\ q_z = k_i\hbar\omega/(2E), \end{cases} \qquad (2)$$

where k_i is a wave number of the incident neutron, E is incident neutron's energy, $\hbar\omega$ is transferred energy. Substituting vector components (Eq.2) into the dispersion relation (Eq.1), and replacing the variables $\theta_0 = \frac{E}{Ak_i^2}$, $\theta_{Bx} = \frac{k_{sx}}{k_i}$, $\theta_C^2 = \theta_0^2 - \frac{\Delta}{Ak_i^2}$, $\tilde{\omega} = \frac{\omega}{2E}$, and meeting the conservation of energy conditions: $\omega - E_q = 0$, $\omega + E_{-q} = 0$ [1], one derives two quadratic equations:

$$\begin{aligned} (\tilde{\omega} - \theta_0)^2 + (\theta_x - \theta_{Bx})^2 &= \theta_C^2, \\ (\tilde{\omega} + \theta_0)^2 + (\theta_x + \theta_{Bx})^2 &= \theta_C^2. \end{aligned} \qquad (3)$$

We can visualize these equations in the form of two spheres in the space of scattering angle - transferred energy (Fig. 1):

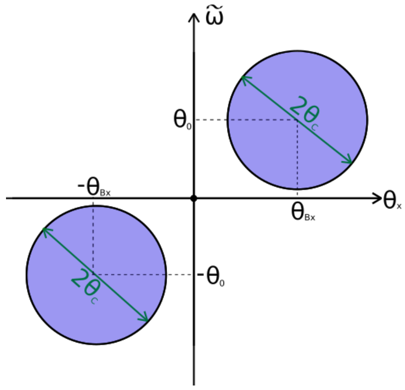

Fig. 1. Graphical representation of Eqs.3

The small-angle neutron scattering cross-section is obtained by means of integration of the cross-section along the transferred energy and taking into account the geometric scattering factor. We show that the cut-off angle squared depends linearly on the external magnetic field. The intensity of cross section at the Brag angle tends to infinity at $H = H_{C2}$ and is strongly suppressed by the field inverse proportionally to $(H - H_{C2})$.

These results allow us to model data of small-angle polarized neutron scattering in spin waves in helimagnets with Dzyaloshinskii-Moriya interaction.

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Incommensurate magnetic order in CoO nanoparticles revealed by neutron diffraction

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The CoO nanoparticles can exist with crystal structure of wurtzite and zinc-blende, unlike the rocksalt structure, which is characteristic for the bulk. However, the magnetic structures of the wurtzite and zinc-blende phases remain unknown. The neutron diffraction studies were performed in CoO nanoparticles with wurtzite (~30 nm) and zinc-blende (~15 nm) crystal structures to unravel their magnetic order and its temperature evolution.

The magnetic structure in the wurtzite nanoparticles turned out to be complex with two perpendicular components. One component, with a long-range order within basal plane only, appeared to be incommensurate, of the longitudinal spin wave type. Along the hexagonal axis this incommensurate order has very short correlation length, about 5-6 Å. The temperature dependence of the incommensurate magnetic moment confirms two-dimensional character.

Another, perpendicular component of the magnetic moment, aligned along the hexagonal axis, is commensurate with antiferromagnetic order known as the 2-th type for wurtzite structure.

In contrast to the wurtzite nanoparticles the magnetic order in the zinc-blende nanoparticles appeared to be commensurate, antiferromagnetic, corresponding to the 3-th type of magnetic ordering in the fcc lattice similar to the bulk. Magnetic moment is aligned along a cube edge.

The incommensurate magnetic structure in the nanoparticles is quite unusual phenomenon and probably caused by the "stalking faults" type defects in the anisotropic crystal structure of wurtzite at nanoscale.

Raman scattering study of the magnetic dynamics in $PbFeBO_4$ induced by the Dzyaloshinskii-Moriya interaction

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The family of $PbMBO_4$ compounds with M = Fe, Mn, Cr was synthesized by Park et al in 2003 [1], where their static magnetic properties and magnetic structures of powdered samples were determined. All three crystals are isostructural; however, they have different magnetic structures. $PbFeBO_4$ belongs to the orthorhombic crystal system with space group *Pnma* (#62, Z = 4) with a = 7.00, b = 5.94, c = 8.33 Å. Fe^{3+} (S = 5/2) ions occupy 4*a* positions inside edge-shared oxygen octahedra forming one-dimensional chains. One-dimensional magnetic structure was suggested in [1], followed by magnetic and dielectric studies of the single crystals [2] where no signs of short-ordering at T = 250 K was found. A discernible kink in the magnetic susceptibility curves for one of the hard axes was observed at the transition temperature T_N = 114 K and this result remained unexplained up to now.

In this talk, we present results of the Raman scattering study of $PbFeBO_4$ in para- and antiferromagnetic phases, focusing on magnetic excitations. In particular, we will discuss the extinction of the quasi-elastic scattering in the ordered phase [3]; appearance of a high-frequency line around 100 cm^{-1}, which we assign to a one-magnon excitation induced by the Dzyaloshinskii-Moriya (DM) interaction, and the two-magnon excitation in FeO_6 chains. Experimental results are supported by both the magnetic symmetry analysis, allowing us to explain susceptibility anomaly, and calculations within the linear spin-wave theory (LSWT) considering four exchange paths (including the DM interaction) and the single-ion anisotropy. Static magnetic properties were also calculated within simulated annealing procedure.

This research is supported by the Russian science foundation grant No. 16-12-10456 and RFBR grants No. 15-02-04222 and No. 15-32-20613.

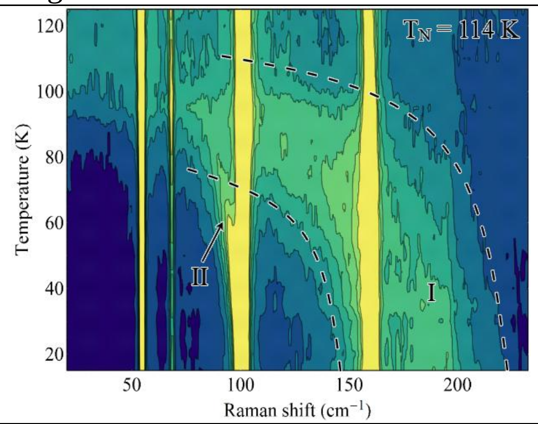

Figure 1. Temperature dependence of the low-frequency Raman spectra in the $a(bb)a$ polarization. I – the two-magnon band; II – the one-magon excitation due to the DM interaction.

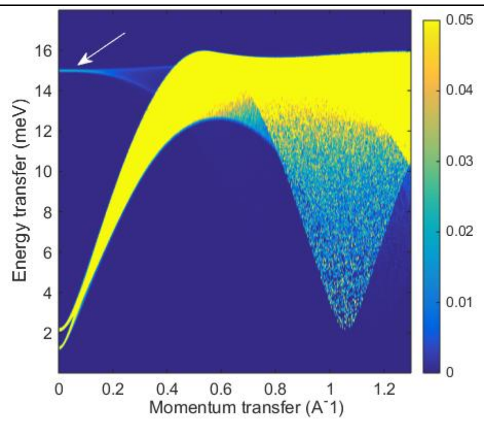

Figure 2. Calculated spin-wave powder-averaged dispersion curves. A weak mode due to the DM interaction close to the Brillouin zone center is marked by an arrow.

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The diffraction study of new low-dimensional spin frustrated chiral $MnSnTeO_6$

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In the quasi-two-dimensional magnets with acentric (chiral) crystal structure and a triangular lattice of magnetic atoms in a layer, the competition between exchange interactions, frustrations and anisotropy can revolutionary affect the fundamental mechanisms of ordering and the corresponding phase transitions. Low-dimensional spin frustrated systems often assume noncollinear incommensurate spin orderings in order to reduce the degree of their spin frustration.

Such chiral type of structure is inherent in $MnSb_2O_6$, a magnet with a chiral crystal and a cycloidal magnetic structure, a multiferroic with a unique ferroelectric switching mechanism [1,2].

We synthesized a new compound $MnSnTeO_6$ with a similar layered trigonal structure *P321* (Fig. 1). Unfortunately, the atomic scattering factors Sn and Te are very close not only to X-rays, but also to neutrons, so it is difficult to directly determine their location in the non-equivalent positions. Nevertheless, we managed to do this in terms of the bonds length with oxygen, since they are larger in tin than in tellurium. Finally, the distribution of Mn-Sn-Te cations by four non-equivalent octahedral sites is established (Fig. 2). Our $MnSnTeO_6$ is a strictly isoelectronic phase with $MnSb_2O_6$, so one would expect a similarity between them.

$MnSnTeO_6$ turned out to be a unique chiral object, one of the distinguishing features of which is the double-charged cation of Mn. A model of a magnetic incommensurate spiral structure of $MnSnTeO_6$ ordered along the direction of layers stacking with the vector $k = (0, 0, 0.183)$, which coincides with the accuracy with a vector of $MnSb_2O_6$ [1], is constructed. $MnSnTeO_6$ magnetic structure refined from neutron diffraction data is very different to that of another family of materials with hereditary cycloidal magnetic chirality, langasite, with the same crystalline symmetry of *P321*.

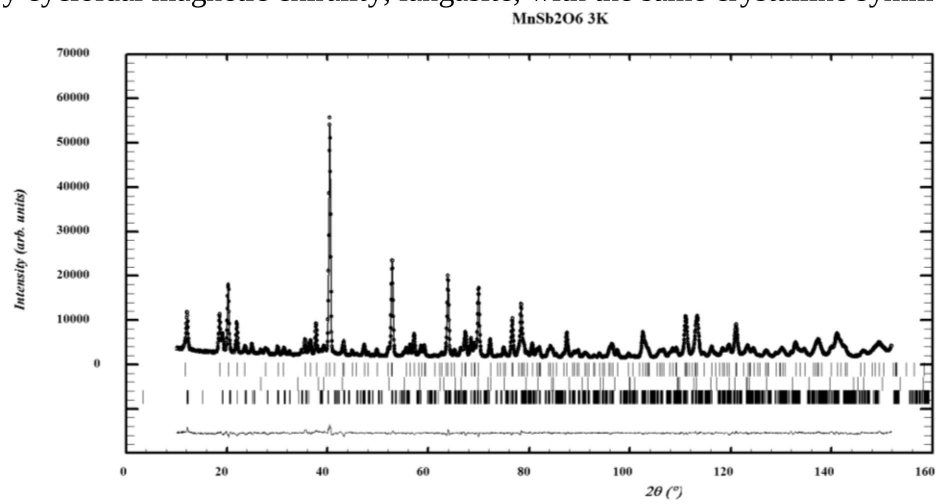

Fig.1 Rietveld refinement against neutron powder diffraction data measured at 3 K, tick marks indicate the nuclear reflexes $MnSnTeO_6$ and impurity SnO_2 (5%), and magnetic peaks, respectively. The measured and calculated profiles are shown with dots and a continuous line, respectively, and a difference curve (observed-calculated) is shown at the bottom.

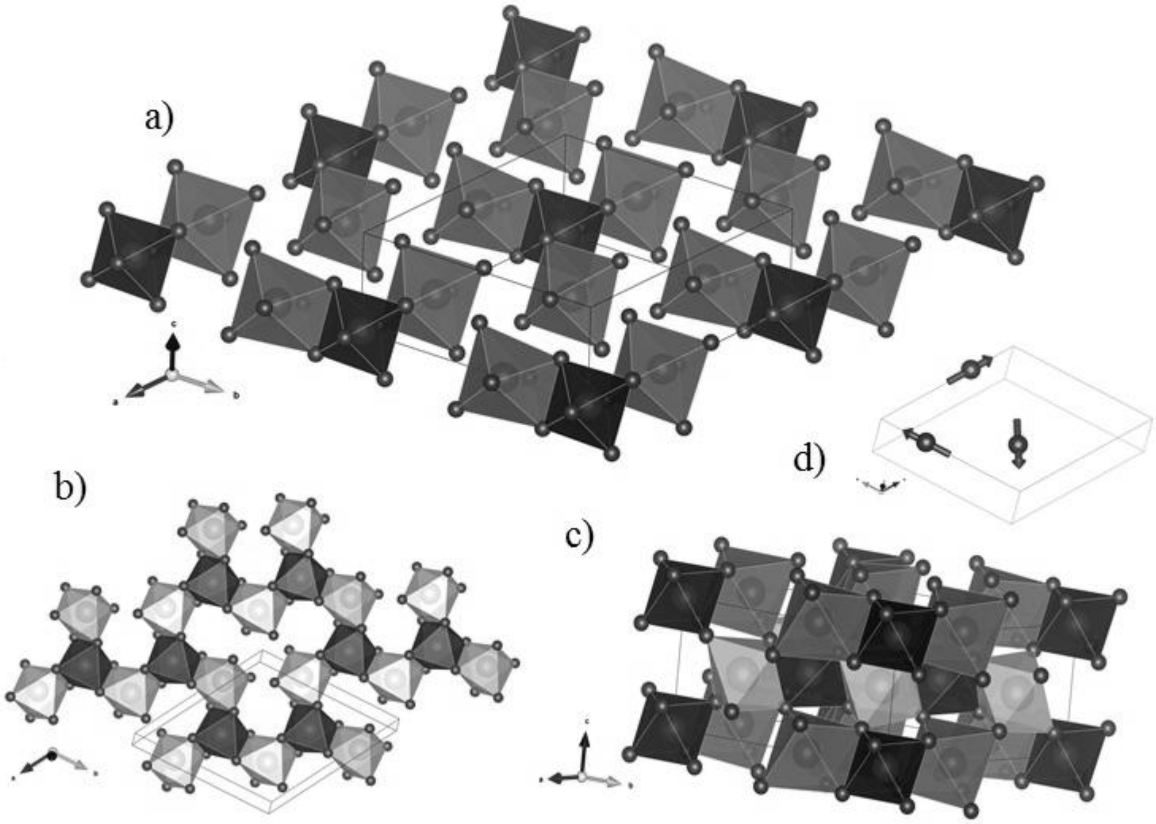

Fig.2 Crystal structure of $MnSnTeO_6$.
a) z = 0 layer of manganese triangles with connected TeO_6 octahedra; b) z = 1/2 layer of SnO_6 and TeO_6 octahedra; c) three-dimensional projection of the crystal; d) element of magnetic structure corresponding to the triplet of the nearest Mn atoms.

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Electric field gradients in *B20 compounds*: Experiment and *ab initio* calculation

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Monosilicides and monogermanides with a noncentrosymmetric B20-type crystal structure continue to attract considerable interest, mostly because of their exotic magnetic properties. As an example, MnSi can be mentioned, where due to the lack of inversion center, the Dzyaloshinskii-Moriya interaction is realized, which leads to a long-period helimagnetic structure. Monogermanides that are less well understood than monosilicides, exhibit even more rich magnetic and electronic phenomena. For instance, the coexistence of unconventional superconductivity and long-range ferromagnetism has recently been observed in high-pressure-synthesized rhodium germanide RhGe [1].

Here, we report on our experimental measurements and *ab initio* calculations of some B20 monogermanides, including the metastable high-pressures phase RhGe. Among other characteristics, we compare the experimental and theoretical electric field gradients (EFG) in metal and metalloid sublattices. The experimental data are obtained by means of the time-differential perturbed angular γγ-correlation (TDPAC) technique on ^{111}In/^{111}Cd probe nuclei. The calculations are made using the FP-LAPW+lo method (Wien2k package) and the first-principles pseudopotential method (QuantumEspresso package). We demonstrate, in particular, that the ^{111}Cd probes are most likely to occupy the metalloid sites in the B20 lattice.

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Observation of a nonreciprocal signal in ferromagnetic resonance in multiferroic $GaFeO_3$

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If the time reversal symmetry and space inversion symmetry are simultaneously broken in a matter, the linear magnetoelectric (ME) effect may appear. The linear ME materials also show a nonreciprocal response like directional dichroism to an electromagnetic wave. The origin of the linear ME effect and nonreciprocal electromagnetic-wave response is explained by magnetic multipoles like toroidal moment [1].

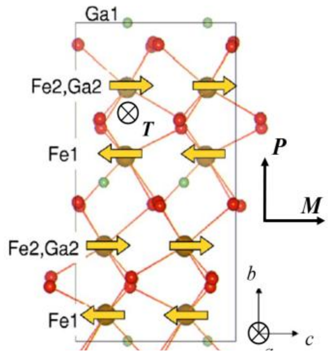

Fig.1: Crystal strucuture of $GaFeO_3$ projected along the a *axis. Yellow arrows show the magnetic moments of Fe ion.*

$GaFeO_3$ is a polar ferrimagnet with a magnetic space group $Pc'2_1'n$. Because the spontaneous polarization ***P*** exists along the *b* axis and magnetic easy axis is the *c* axis, toroidal moment ***T*** appears along the *a* axis, as shown in Fig. 1. This compound shows a linear ME effect and directional dichroism [2,3].

Recently, nonreciprocal responses of quasi-particles like a magnon are reported in chiral magnets and multiferroics[4]. $GaFeO_3$ is also expected to show directional dichroism in a magnon because of its ferrotoroidic nature[1].

Figure 2 shows ferromagnetic resonance (FMR) of 240 GHz microwave at 100 K. Red and blue lines show the data in positive and negative magnetic fields ***H*** // *c*, respectively. We observed a difference in absorption of the microwave between $H > 0$ and $H < 0$. The nonreciprocal response to microwave of the ferrotoroidic material is attributable to the interference between magnetic- and electric- dipole processes of magnon excitation.

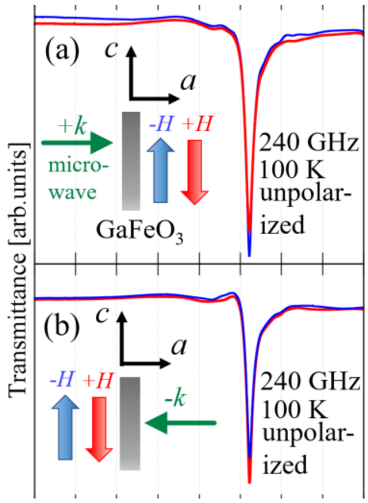

Fig.2: H- *and* k- *depenence of FMR spectrum measured at a frequency of 240 GHz using an unpolarized microwave. Incident microwave wavevectors* k *shown by green arrows are (a) parallel and (b) antiparallel to the* a *axis, respectively.*

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Dynamics of chiral soliton lattice under an electric field and its magnetic dependence

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Recently, chiral soliton lattice (CSL) has attracted much attention. CSL is formed by competition between the Zeeman energy and the antisymmetric Dzyaloshinskii-Moriya (DM) interaction. When one dimensional classical spin chain has the DM interaction, a chiral helical magnet is stabilized. When an external magnetic field is applied parallel to the spin axis, the period of the spin structure continuously becomes longer; this tunable super lattice is called the CSL. Many experimental and theoretical studies about the CSL have been carried out [1-2].

There are fascinating features of CSL; for example, one can easily control the response of conduction electrons by applying the external magnetic field on the CSL. It is also expected that torque on the CSL induced by spin-polarized electric current can be controlled. This torque causes the dynamics of domain walls and will have a large impact on application because of its tunable feature. However, the effects on torques by changing the spin structure have not been well studied. There is a previous study which reveals the dynamics of the CSL under an electrical current [3]. It is shown that the CSL moves at a certain velocity under the electrical current after some relaxation time. However, this work does not consider the effect of magnetic field on the torque. Therefore, the magnetic field dependence of the dynamics of the CSL is still unknown.

In this presentation, we clarify the magnetic field dependence of the velocity of CSL starting from a microscopic model and using the rigorous SU(2) spin gauge transformation[4]. We will show that the torque from conduction electrons depends on the magnetic field and dynamics can be controlled. It turns out that the velocity of the CSL becomes slower when the period becomes longer. We also mention a relation between the velocity and its magnetic resistance.

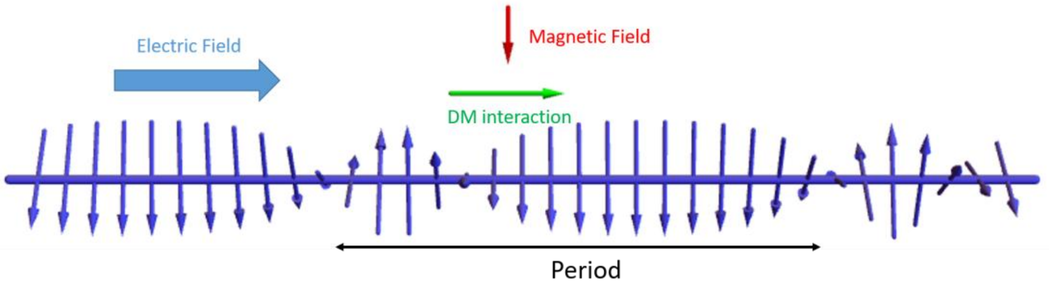

Fig. 1 Schematic picture of a chiral soliton lattice

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