Experimental report

05/04/2019

Proposal: **5-41-918**

Council: 4/2017

Title: Search for skyrmionic lattice in $EuNiGe_3$

Research area: Physics

This proposal is a new proposal

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Samples: $EuNiGe_3$

Instrument	Requested days	Allocated days	From	To
D33	4	3	09/04/2018	12/04/2018

Abstract:

Skyrmions have been found in cubic helimagnets and in ultrathin films with surface induced Dzyaloshinskii-Moriya interaction (DMI). In bulk, skyrmionic phases are observed in a tiny temperature range near ordering temperature. Theoretically, skyrmion-lattice ground-states have been predicted to exist in crystals from certain Laue classes. Experimentally, these skyrmion phases have yet not been observed. We have identified tetragonal crystals of $EuNiGe_3$ as suitable bulk material to observe skyrmionic ground-state phases, in particular field-driven skyrmion lattices. The presence of the skyrmion lattice (at high magnetic fields) and remanent Dzyaloshinskii spiral is suggested to be verified via neutron small-angle diffraction at various magnetic fields of up to 4 T below 10 K and at lower fields in the intermediate temperature range between 10 and 14 K.

Chiral magnetism in acentric magnetic crystals has become a topical research subject because of the existence of skyrmions, two-dimensional topological solitons [1, 2] and skyrmionic phases which are stabilized by asymmetric Dzyaloshinskii-Moriya (DM) exchange. In bulk, evidence for skyrmionic phases has been found only in a tiny temperature range near ordering temperature. The original work of skyrmions [1] predicted that crystals from certain Laue classes may exhibit skyrmion-lattice ground states as field-driven states, because the inhomogeneous chiral DMIs arise only in two spatial directions.

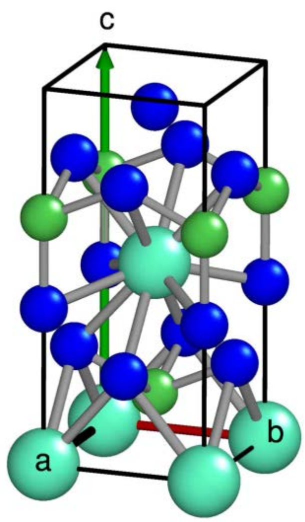

Fig 1: Schematic representation of the crystal structure of $EuNiGe_3$. Large atoms are Eu^{2+}.

Skyrmion-lattice leads to new, usually long periodicities that can be conveniently studied by a small angle neutron diffraction. In this experiment using D33 we have measured $EuNiGe_3$ single crystal that has identified as a suitable bulk material to host skyrmion ground states. $EuNiGe_3$ belongs to a large class of ternary rare-earth-transition-metal tetragonal compounds (Fig. 1) with space group I4mm (#107). Previous experiments on single-crystals [3,4] have shown a complex antiferromagnetic behaviour, with several field-driven phases that displays various hallmarks of chiral magnetism as expected from its crystal structure. The magnetic phase diagram for field applied along the c-axis is shown in Fig. 2.

In previous bulk experiments it was shown that accessible fields less than 6 T allows to reach the "spin-flip"', *i.e.*, the field-induced fully spin-polarized/ferromagnetic state. There is very notable anisotropic behaviour of the single-crystals supported by density-functional theory calculations [5]. Moreover, Eu-151 Mössbauer spectroscopy has provided clear evidence for an inhomogeneous magnetic state, *e.g.* a spin-density wave or a spiral magnetism [3]. Rough estimates of magnetic coupling strengths suggest a spiral wavelength of a few times 10 nm.

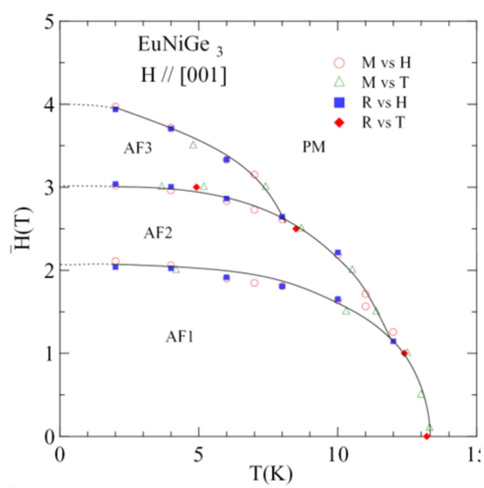

Fig 2: Magnetic phase diagrams of $EuNiGe_3$ for field applied along the tetragonal axis. After [3]. AF1 is a spiral antiferromagnetic phase with propagation k=(1/4, δ, 0), δ = 0, AF2 has δ = 0.072 [4]. AF3 or AF2 are anticipated to be skyrmion phases. For the AF3 phase no Bragg reflections have been observed up to date.

Due to a large absorption of Eu we have measured single crystals in a form of thin plates. However, even with the thickness of 0.3 mm the transmission was of the order of few %. In most of the cases we have wavelength of 4.6 Å and pinhole of 2 mm. The magnetic field has been applied along the c axis and the sample has been rotated around vertical axis perpendicular to the field. We have performed an extensive search at various places of the magnetic phase diagram between 20 K and in fields up to 4.5 T. As measurements with the central detector at 12 m distance die not lead to any observations, we have continued with detector positions set to the shortest distances from the sample (Det1 = 1.182 m

Det2 = 1.960 m). In this configuration we were sensitive to magnetic Bragg reflections expected for AF1 and AF2 phases. In Fig. 3 (left panels) we show representative SANS signals obtained at low temperatures either in zero field or in field applied along the tetragonal axis. We were able to identify apart from known magnetic Bragg reflections belonging to AF1 and AF2 phases also Bragg reflections of the AF3 phase. These appear at the same positions as reflections of the AF1 phase and are therefore indexable with propagation vector k(AF1) =(1/4, δ, 0), δ = 0. However, in addition to those we observe in the AF3 state also new, previously not observed Bragg reflections (see Fig. 3c). Let us also note that the phase transitions are not step-like and an appreciable range of fields/temperatures exists where magnetic reflections belonging to different phases coexist. In addition, surprisingly, the AF3 reflections are still present well above the magnetic phase transition of 4 T. An indexation attempt shows that the new reflections can be explained by √2 multiplication of periodicities leading to AF1 reflections. However, we are not able to index all the reflections using a single propagation vector. In fact, it looks that there are two sets of reflections, rotated by ~ 22 degrees. One explanation would be a second grain in the crystal.

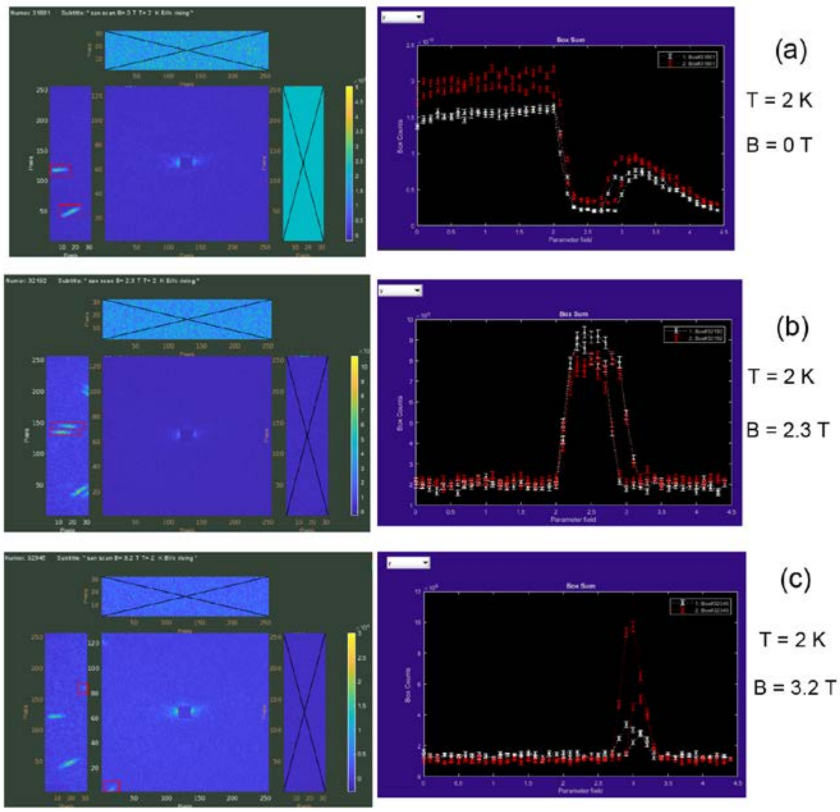

Fig 3: Representative SANS results obtained at 2 K in (a) zero field, (b) at 2.3 T and (c) at 3.2 T applied along the c axis (left panels). Different magnetic Bragg reflections are visible, belonging to AF1, AF2 and AF3 phases respectively. The field dependences of box-type integrations as indicated in left panels is shown on the right.

In conclusion, we could not observe the anticipated skyrmion lattice neither at low temperatures in regions close to the critical field nor at elevated temperatures and fields around the ordering temperature. We were, however, able to map the phase diagram in detail and to identify magnetic reflections belonging to the AF3 phase showing that the magnetic phases coexist in critical regions.

References:

[1] A. N. Bogdanov, D. A. Yablonskii, *Zh. Eksp. Teor. Fiz*, **95**, 182 (1989).
[2] U. K. Rößler, A. N. Bogdanov, C. Pfleiderer, *Nature* **442**, 797 (2006).
[3] A. Maurya, P. Bonville, A. Thamizavel, S. K. Dhar, *J. Phys.:CM* **20**, 216001 (2014).
[4] X. Fabreges et al. Phys. Rev. B **93,** 214414 (2016).
[5] U. K. Rößler, unpublished (2015)