Magnetic structure analysis of $Eu(Al_{0.6}Ga_{0.4})_4$ by polarized neutron scattering

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Magnetic skyrmions, i.e., vortex-like swirling spin texture with topologically stable particle-like nature, are attracting attention as a source of large fictitious magnetic field to the electrons. Since the amplitude of the fictitious magnetic field is proportional to the skyrmion density, a small size of skyrmion is expected to generate large electromagnetic responses. Until recently, skyrmions have been found mainly in magnets with broken inversion symmetry, with diameters ranging from tens to hundreds of nanometers. Very recently, a few nanometer-sized skyrmions were observed in Gd-based intermetallic compounds with inversion symmetry, exhibiting giant topological Hall effect [1,2]. It has been newly proposed that magnetic interactions via itinerant electrons play an important role to stabilize such nanometric skyrmions.

As a candidate material in which the latter mechanism works, we recently investigated the magnetic structures of a centrosymmetric tetragonal magnet $EuAl_4$. This compound is metallic, and the magnetism is governed by the Eu^{2+} ions. In our previous neutron experiments, we have revealed the appearance of rhombic and square lattices of skyrmions with a diameter of 3.5 nm under $H \parallel c$ [3]. We also found that the observed H-induced transition between the two skyrmion lattice states can be reproduced by the theoretical simulation for the square lattice system based on the effective spin Hamiltonian derived from the Kondo lattice model. This suggests that the itinerant-electron-mediated mechanism contributes to the skyrmion formation in $EuAl_4$.

For the above mechanism, it is theoretically predicted that the stability of skyrmion phase strongly depends on the magnetic anisotropy. A series of $Eu(Al_{1-x}Ga_x)_4$, in which the magnetic anisotropy changes from easy-axis type to easy-plane type upon increasing the Ga-substitution ratio *x*, is expected as a platform to elucidate the effect of magnetic anisotropy on the skyrmion formation. In the present study, we performed polarized neutron scattering experiment at zero field on $Eu(Al_{0.6}Ga_{0.4})_4$, which is characterized by easy-plane type anisotropy, to identify the magnetic structures for each phases (Fig. 1(a)). We measured the temperature dependence of the (δ, 0, 0) and (δ, 0, 4) line scan profiles for the magnetic Bragg reflection at (q, 0, 0) and separately detected the spin-flip (SF) and non-spin-flip (NSF) scattering signals as shown in Fig. 1(b). We confirmed that *ab*-cycloidal spin state is formed at the lowest temperature (phase I), which changed into screw (phase II) and sinusoidal spin states (phase III) on increasing temperature. We are now performing the theoretical simulation to explain the variation of magnetic structures between $EuAl_4$ (easy-axis) and $Eu(Al_{0.6}Ga_{0.4})_4$ (easy-plane), and aim to clarify the effect of the magnetic anisotropy on the stability of magnetic skyrmion state.

[1] T. Kurumaji *et al.*, *Science* **365**, 914 (2019).
[2] N. D. Khanh *et al.*, *Nat. Nanotech.* **15**, 444 (2020).
[3] R. Takagi *et al.*, Nat. Commun. **13**, 1472 (2022).

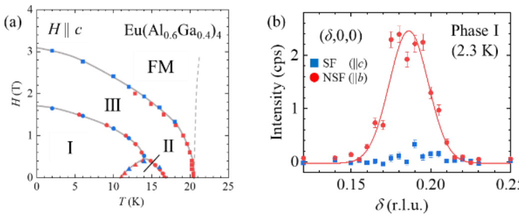

Fig. 1. (a) Magnetic phase diagram of $Eu(Al_{0.6}Ga_{0.4})_4$. (b) (δ, 0, 0) line scan profiles of SF and NSF scatterings for phase I at zero field.