Spin order and fluctuations in the EuAl$_4$ and EuGa$_4$ topological antiferromagnets: A $\mu$SR study

X. Y. Zhu,$^{1,*}$ H. Zhang,$^{1,**}$ D. J. Gawryluk,$^2$ Z. X. Zhen,$^1$ B. C. Yu,$^1$ S. L. Ju,$^3$ W. Xie,$^4$ D. M. Jiang,$^1$ W. J. Cheng,$^1$ Y. Xu,$^1$ M. Shi,$^3$ E. Pomjakushina,$^8$ Q. F. Zhan,$^1$ T. Shiroka,$^5,6,1$ and T. Shang$^{1,*}$

$^1$Key Laboratory of Polar Materials and Devices (MOE), School of Physics and Electronic Science, East China Normal University, Shanghai 200241, China
$^2$Laboratory for Multiscale Materials Experiments, Paul Scherrer Institut, Villigen CH-5232, Switzerland
$^3$Swiss Light Source, Paul Scherrer Institut, Villigen CH-5232, Switzerland
$^4$DESY, Notkestraße 85, D-22607 Hamburg, Germany
$^5$Laboratory for Muon-Spin Spectroscopy, Paul Scherrer Institut, Villigen PSI, Switzerland
$^6$Laboratorium für Festkörperphysik, ETH Zürich, CH-8093 Zürich, Switzerland

(Dated: January 10, 2022)

EuAl$_4$ and EuGa$_4$ are two candidate materials for studying the interplay between correlated-electron phenomena, topological spin textures, and topologically nontrivial bands. Both compounds crystallize in a centrosymmetric tetragonal BaAl$_4$-type structure (space group I4/mmm) and show antiferromagnetic (AFM) order below $T_N = 15.6$ and 16.4 K, respectively. Here, we report on systematic muon-spin rotation and relaxation ($\mu$SR) studies of the magnetic properties of EuAl$_4$ and EuGa$_4$ single crystals at a microscopic level. Transverse-field $\mu$SR measurements, spanning a wide temperature range (from 1.5 to 50 K), show clear bulk AFM transitions, with an almost 100% magnetic volume fraction in both cases. Zero-field $\mu$SR measurements, covering both the AFM and the paramagnetic (PM) states, reveal internal magnetic fields $B_{\mu}(0) = 0.33$ T and 0.89 T in EuAl$_4$ and EuGa$_4$, respectively. The transverse muon-spin relaxation rate $\lambda_{\perp}$, a measure of the internal field distribution at the muon-stopping site, shows a contrasting behavior. In EuGa$_4$, it decreases with lowering the temperature, reaching its minimum at zero temperature, $\lambda_{\perp}(0) = 0.71 \mu s^{-1}$. In EuAl$_4$, it increases significantly below $T_N$, to reach 58 $\mu s^{-1}$ at 1.5 K, most likely reflecting the complex magnetic structure and the competing interactions in the AFM state of EuAl$_4$. In both compounds, the temperature-dependent longitudinal muon-spin relaxation $\lambda_{\parallel}(T)$, an indication of the rate of spin fluctuations, diverges near the onset of AFM order, followed by a significant drop at $T < T_N$. In the AFM state, spin fluctuations are much stronger in EuAl$_4$ than in EuGa$_4$, while being comparable in the PM state. The evidence of robust spin fluctuations against the external magnetic fields provided by $\mu$SR may offer new insights into the origin of the topological Hall effect and the possible magnetic skyrmions in the EuAl$_4$ and EuGa$_4$ compounds.

I. INTRODUCTION

Topological materials are at the forefront of quantum matter and material science research due to their great potential for applications [1, 2]. Recently, the discovery of nontrivial band topology and extremely large magnetoresistance in the BaAl$_4$ compound has stimulated considerable interest in this family of materials [3]. The tetragonal BaAl$_4$-type structure with a space group I4/mmm (No. 139) represents the prototype for many binary- and ternary-derived compounds [4], as e.g., heavy-fermion compounds and iron-based high-$T_c$ superconductors.

Upon replacing Ba with Sr or Eu, or when replacing Al with Ga, all AE(Al,Ga)$_4$ (AE = Sr, Ba, and Eu) crystallize in the same tetragonal structure, while Ca(Al,Ga)$_4$ adopts a monoclinic crystal structure with a space group C2/m (No. 12) [3, 5]. Among these materials, the Eu-4f electrons bring new intriguing aspects to the topology. Both EuAl$_4$ and EuGa$_4$ are antiferromagnets below their critical temperatures $T_N = 15.6$, and 16.4 K, respectively, with the former also undergoing a CDW transition at $T_{\text{CDW}} \sim 140$ K [6–12]. Further, while EuGa$_4$ exhibits only one antiferromagnetic (AFM) transition, EuAl$_4$ undergoes four subsequent AFM transitions below $T_N$. More interestingly, by applying a magnetic field along the c-axis, both EuAl$_4$ and EuGa$_4$ undergo a series of metamagnetic transitions in the AFM state [6, 7, 10]. Within a field range of $\sim 1–2.5$ T (EuAl$_4$) or $\sim 4–7$ T (EuGa$_4$), a clear hump-like anomaly is observed in the Hall resistivity, most likely a manifestation of the topological Hall effect (THE) [6, 7]. Very recently, a THE has been observed also in Al-doped EuGa$_4$ [13], which exhibits comparable critical fields to EuAl$_4$ [6].

The topological Hall effect is considered to be the hallmark of spin textures with a finite scalar spin chirality. Such topological spin textures usually exhibit a nonzero Berry phase, here acting as an effective magnetic field, giving rise to the topological Hall resistivity [14]. THE is frequently observed in magnetic materials with non-coplanar spin textures, such as magnetic skyrmions [15–25]. Skyrmions are one of the most intriguing topologically nontrivial spin textures that can be easily manipulated [26], hence holding a promise for diverse applications, such as high-density spintronics [27, 28]. THE has been observed mostly in magnetic compounds whose crystal structure lacks an inversion center, while centrosymmetric compounds that host magnetic skyrmions are rare [15–19, 29, 30]. Eu(Al,Ga)$_4$ represent such rare cases where to look for the possible existence of magnetic skyrmions [6, 7, 13]. According to neutron diffraction studies, in the AFM state, the magnetic q-vector of EuAl$_4$ changes from $q_1 = (0.085, 0.085, 0)$ at $T_N = 13.5$ K to $q_2 = (0.170, 0, 0)$ at 11.5 K and slightly to $q_3 = (0.194, 0, 0)$ at 4.3 K [31]. Unlike the complex incommensurate transitions observed in EuAl$_4$, the AFM structure of EuGa$_4$ is described by a simple $q = (0, 0, 0)$ magnetic vector, with the Eu moments lying in the basal ab-plane [32]. Noncollinear spins with incommensurate propagation vectors have been reported also in the isosstructural EuGa$_2$Al$_2$ [13].

As an extremely sensitive magnetic probe at a microscopic level, the muon-spin rotation and relaxation ($\mu$SR) technique lends itself naturally to studying the temperature evolution of the magnetic properties of EuAl$_4$ and EuGa$_4$ single crystals. As shown in detail below, we report: i) the intrinsic fields at the muon implantation sites in EuAl$_4$ and EuGa$_4$ across the respective phase diagrams in the absence of external magnetic fields; ii) the magnetic volume fraction in the AFM state; iii) evidence of strong spin fluctuations.
II. EXPERIMENTAL DETAILS

Single crystals of EuAl$_4$ and EuGa$_4$ were grown by a molten Al- and Ga flux method, respectively, the details of growth being reported elsewhere [6, 7]. The crystal orientation was checked by x-ray diffraction (XRD) measurements using a Bruker D8 diffractometer with Cu K$_\alpha$ radiation. The magnetic susceptibility measurements were performed on a Quantum Design magnetic properties measurement system (MPMS) with the applied magnetic field along the c-axis.

µSR experiments were carried out at the general-purpose surface-muon (GPS) instrument at the ΠM3 beam line of the Swiss muon source (Swiss) at Paul Scherrer Institut (PSI) in Villigen, Switzerland. In this study, we performed three kinds of experiments: weak transverse-field (wTF)-µSR, zero-field (ZF)-, and longitudinal-field (LF)-µSR measurements. As to the former, we could determine the temperature evolution of the magnetic volume fraction. As to the latter two, we aimed at studying the temperature evolution of the magnetically ordered phase and the dynamics of spin fluctuations.

The aligned EuAl$_4$ and EuGa$_4$ crystals were positioned on a thin aluminum tape, with their c-axes parallel to the muon-momentum direction, i.e., $p_\parallel || c$ [see inset in Fig. 1(a)]. For the wTF-µSR measurements, the applied magnetic field $B_{\text{app}}$ was perpendicular to the muon-spin direction (i.e., $B_{\text{app}} \perp S_\gamma$), while it was parallel for the LF-µSR measurements (i.e., $B_{\text{app}} \parallel S_\gamma$). In both wTF- and LF-µSR cases, the crystals were cooled in an applied magnetic field down to the base temperature (i.e., 1.5 K). For the ZF-µSR measurements, to exclude the possibility of stray magnetic fields, the magnets were degaussed before the measurements. All the µSR spectra were collected upon heating and were analyzed by means of the muSfit software package [33].

III. RESULTS AND DISCUSSION

A. wTF-µSR

The magnetic transition temperatures $T_N$ and the evolution with temperature of the magnetic volume fraction in EuAl$_4$ and EuGa$_4$ single crystals were established by means of wTF-µSR measurements. A weak transverse field of 5 mT was applied perpendicular to the initial muon-spin direction in the PM state, where it leads to oscillations, as shown in Fig. 1. In the long-range ordered AFM state (i.e., 1.5 K), the applied 5-mT field is much smaller than the internal fields. As a consequence, upon entering the AFM state, muon spins precess with frequencies that reflect the internal fields at the muon-stopping sites rather than the weak applied field. Normally, the magnetic order leads to a very fast muon-spin depolarization in the first tenths of $\mu$s (see also the ZF-µSR spectra in the insets of Fig. 3). Therefore, the wTF-µSR spectra can be described by the function:

$$A_{\text{wTF}}(t) = A_{\text{NM}} \cos(\gamma / \mu B_{\text{int}} t + \phi) \cdot e^{-\lambda t},$$

where $A_{\text{NM}}$ is the initial beam-spin asymmetry (i.e., the amplitude of the oscillation) for muons implanted in the nonmagnetic (NM) or PM fraction of EuAl$_4$ and EuGa$_4$ single crystals; $\gamma / \mu B_{\text{int}}$ is the muon precession frequency, with $\gamma / \mu = 2\pi \times 135.5$ MHz/T the muon gyromagnetic ratio and $B_{\text{int}}$ the local field sensed by muons (here almost identical to the applied magnetic field, i.e., $B_{\text{app}} \sim 5$ mT); $\phi$ is the initial phase, and $\lambda$ is the muon-spin relaxation rate. Note that, in the AFM state, the very fast µSR relaxation was excluded and only the residual slow-relaxing asymmetry was analyzed (see the 1.5-K dataset in Fig. 1).

Figure 2 summarizes the resulting wTF-µSR asymmetry values $A_{\text{NM}}$ as a function of temperature. In the PM state, all the implanted muons precess at the same frequency $\gamma / \mu B_{\text{int}}$. As the temperature approaches $T_N$, only the muons implanted in the remaining PM/NM phase precess at the frequency $\gamma / \mu B_{\text{int}}$ here reflected in a reduced oscillation amplitude. The PM (or NM) sample fraction is determined from the oscillation amplitude. In both EuAl$_4$ and EuGa$_4$, $A_{\text{NM}}$ starts to decrease near the onset of AFM order, where
also the magnetic susceptibilities show clear transitions. Although EuAl₄ undergoes four successive AFM transitions [indicated by vertical arrows in Fig. 2(a)], $A_{\text{int}}(T)$ does not capture them individually, as it is sensitive only to the global PM (or NM) volume fraction. The temperature evolution of the magnetic volume fraction can be derived from $V_{\text{mag}}(T) = 1 - A_{\text{int}}(T)/A_{\text{int}}(T > T_N)$. The $V_{\text{mag}}(T)$ values are summarized in the insets of Fig. 2(a) and 2(b) for EuAl₄ and EuGa₄, respectively. To determine the magnetic volume fraction $V_{\text{mag}}$, the average magnetic transition temperature $T_N$, and the transition width $\Delta T$, $V_{\text{mag}}(T)$ data were fitted using the phenomenological function:

$$V_{\text{mag}}(T) = V_{\text{mag}}(0) \left(1 - \text{erf}\left(\frac{T - T_N}{\sqrt{2\Delta T}}\right)\right),$$

where erf($T$) is the error function. As shown by solid lines in the insets of Fig. 2, for EuAl₄, we obtain $T_N = 13.9(2)$ K, $\Delta T = 1.4(2)$ K, and $V_{\text{mag}}(0) = 91(2)$%; while for EuGa₄, $T_N = 15.2(3)$ K, $\Delta T = 1.8(2)$ K, and $V_{\text{mag}}(0) = 95(2)$%. Both samples show sharp transitions and can be considered as fully magnetically ordered at low temperatures, indicative of a high sample quality. Note also that, the transition temperatures, as determined from $V_{\text{mag}}(T)$, have their onset at $\sim 16.5$ K and $\sim 16.7$ K for EuAl₄ and EuGa₄, both in very good agreement with the magnetometry data.

B. ZF- and LF-$\mu$SR

To investigate the local magnetic order of EuAl₄ and EuGa₄ single crystals, ZF-$\mu$SR spectra were collected at different temperatures, covering both the PM and AFM states. The time evolution of ZF-$\mu$SR asymmetry, $A_{ZF}(t)$, encodes the local magnetic fields and their distribution at the muon-stopping site. If the electronic magnetic moments fluctuate very fast (typically above $10^{12}$ Hz in the PM state), they do not influence the muon-spin polarization. Randomly oriented slow fluctuating or static moments (below $10^6$ Hz, such as nuclear spins, or electronic moments in spin glasses), give rise to incoherent precessions and a slow depolarization. Conversely, in case of ordered static moments, a fast depolarization and superimposed oscillations, reflecting the coherent precession of the muon spins, are observed [34]. This is clearly demonstrated in Fig. 3, where the time evolution of selected ZF-$\mu$SR spectra for EuAl₄ and EuGa₄ are presented.

In the PM state ($T > T_N$), the $\mu$SR spectra still exhibit a relatively fast muon-spin depolarization ($\sim 2 \mu$s⁻¹), implying the existence of spin fluctuations, here further confirmed by LF-$\mu$SR measurements (see below). In absence of spin fluctuations, the muon-spin depolarization is usually due to the nuclear dipole fields [34], with a typical value of less than 0.1 $\mu$s⁻¹ in EuAl₄ and EuGa₄ [35]. The $\mu$SR spectra in the AFM state ($T < T_N$) are characterized by highly damped oscillations, typical of long-range magnetic order (see insets in Fig. 3), superimposed on a slowly decaying relaxation, observable only at long times. To track these changes across the whole temperature range, the ZF-$\mu$SR spectra of EuAl₄ and EuGa₄ were analyzed using the following model:

$$A_{ZF}(t) = A_1 \cdot \left[\alpha \cos(\gamma_{\mu} B_{\text{int}} t + \phi) \cdot e^{-\lambda_{\perp} t} + (1 - \alpha) \cdot e^{-\lambda_{\parallel} t}\right] + A_2 \cdot e^{-\lambda_{\perp} t}.$$

Here, $\alpha$ and $1 - \alpha$ are the oscillating (i.e., transverse) and nonoscillating (i.e., longitudinal) fractions of the $\mu$SR signal, respectively, whose initial total asymmetry is equal to $A_1$. $\lambda_{\perp}$ and $\lambda_{\parallel}$ represent the transverse and longitudinal relaxation rates, while $A_1$ and $A_2$ represent the asymmetries of the two nonequivalent muon-stopping sites. In EuAl₄, muons stopping at the second site do not undergo any precession, but show only a slow relaxation, here described by $\lambda_{\perp}$. In EuGa₄, a single muon-stopping site is sufficient to describe the ZF-$\mu$SR spectra. Finally, $B_{\text{int}}$, $\phi$, and $\gamma_{\mu}$ are the same as in Eq. (1). Similar expressions have been used to analyze the $\mu$SR data in other Eu-based magnetic materials, most notably, in the Eu₁₂₂ iron pnictides [36, 37].

In polycrystalline materials with a long-range magnetic order, one expects $\alpha = 2/3$, since statistically one third of the muon spins are aligned parallel to the local field direction (i.e., $S_{\mu} || B_{\text{int}}$) and, hence, do not precess. In EuAl₄ and EuGa₄ single crystals, we find $\alpha$ to be 0.87 and 0.46, respectively. Since the ZF-$\mu$SR spectra were collected in a rotated muon-spin configuration (i.e., $S_{\mu} \perp p_{\mu}$), and the c-axis is parallel to the muon momentum (i.e., $c || p_{\mu}$), the internal magnetic fields at the muon-stopping sites should be mostly aligned along the [001]-direction in EuAl₄, but along the [111]-direction in EuGa₄.

The derived fit parameters for both cases are summarized in Fig. 4 and Fig. 5. As can be clearly seen in the top panels, EuAl₄ and EuGa₄ show rather different $B_{\text{int}}(T)$ behaviors. In EuAl₄, the $B_{\text{int}}(T)$ undergoes a sudden drop at $\sim 13$ K, which corresponds to the second AFM transition in the magnetic susceptibility [see Fig. 2(a)]. Conversely, in EuGa₄, $B_{\text{int}}(T)$ resembles the typical mean-field type curve below $T_N$. Since $B_{\text{int}}$ is directly proportional to the magnetic moment, the evolution of $B_{\text{int}}$ reflects that of the magnetic structure. According to neutron scattering studies, in EuAl₄, the magnetic q-vector changes from $q_1 = (0.085, 0.085, 0)$ at $T_N = 13.5$ K

![FIG. 3. Representative ZF-$\mu$SR spectra collected in a transverse muon-spin configuration ($p_{\mu} \perp S_{\mu}$) at temperatures covering both the PM and AFM states for (a) EuAl₄ and (b) EuGa₄, respectively. Insets highlight the short-time spectra, illustrating the coherent oscillations caused by the long-range AFM order. Solid lines through the data are fits to Eq. (3) (see text for details).]
to \( q_2 = (0.170, 0, 0) \) at 11.5 K and slightly to \( q_1 = (0.194, 0, 0) \) at 4.3 K \[31\]. Therefore, we identify the drop of \( B_{\text{int}} \) at 13 K with the critical temperature where the magnetic structure changes from \( q_1 \) to \( q_2 \). At the same time, the modification of magnetic structure from \( q_2 \) to \( q_3 \) is too tiny to have a measurable effect on \( B_{\text{int}} \). By contrast, the AFM structure of EuGa\(_4\) is rather simple \( [\text{its magnetic vector being } q = (0, 0, 0)] \) and it persists down to 2 K \[32\]. As a consequence, in EuGa\(_4\), \( B_{\text{int}} \) decreases monotonically as the temperature increases. In both compounds, \( B_{\text{int}}(T) \) can be modeled by the phenomenological equation:

\[
B_{\text{int}}(T) = B_{\text{int}}(0) \left[ 1 - \left( \frac{T}{T_N} \right)^{\gamma} \right]^{\delta} . \tag{4}
\]

Here, \( B_{\text{int}}(0) \) is the internal magnetic field at zero temperature, while \( \gamma \) and \( \delta \) are two empirical parameters. As indicated by the solid lines in Fig. 4(a) and Fig. 5(a), the above model describes the data reasonably well, yielding the parameters listed in Table I. In EuAl\(_4\), the first AFM phase (AFM1) is characterized by \( B_{\text{int}}(0) = 0.57(5) \) T. The change in magnetic structure lowers \( B_{\text{int}}(0) \) down to 0.33(2) T in the second AFM phase (AFM2). In EuGa\(_4\), \( B_{\text{int}}(T) \) follows the typical mean-field type curve, yielding \( B_{\text{int}}(0) = 0.89(2) \) T. Considering the presence of the same magnetic Eu\(^{2+} \) ions in both cases and the similar lattice parameters, the significantly different \( B_{\text{int}}(0) \) values are most likely attributed to the different muon-stopping sites or to different magnetic structures in EuAl\(_4\) and EuGa\(_4\), the latter having been proved by neutron scattering studies. Indeed, at base temperature, EuAl\(_4\) exhibits a complex incommensurate magnetic structure, while this is commensurate in EuGa\(_4\) \[31, 32\].

The temperature dependence of the transverse and longitudinal \( \mu\)SR relaxation rates \( \lambda_T(T) \) and \( \lambda_L(T) \) are summarized in Figs. 4(b) and (c) for EuAl\(_4\) and in Figs. 5(b) and (c) for EuGa\(_4\), respectively. The transverse relaxation rate \( \lambda_T \) is a measure of the width of static magnetic field distribution at the muon-stopping site and is also affected by dynamical effects, e.g., spin fluctuations. The longitudinal relaxation rate \( \lambda_L \) is determined solely by spin fluctuations. In EuAl\(_4\) and EuGa\(_4\), \( \lambda_T(T) \) exhibits completely opposite behaviors. In EuAl\(_4\) \( [\text{see Fig. 4(b)}] \), \( \lambda_T \) is zero in the PM state, and becomes increasingly prominent as the temperature decreases below \( T_N \), reflecting a more disordered field distribution well inside the AFM state. Such a large \( \lambda_T \) at temperatures far below \( T_N \) is unusual for an antiferromagnet, and implies an increasingly inhomogeneous distribution of local fields in the AFM state of EuAl\(_4\). Thus, at 1.5 K, \( \lambda_T \approx 58(10) \) \( \mu\)s\(^{-1} \), which implies a half-width at half-maximum (HWHM) of field distribution \( \Delta = 68(12) \) mT (here, \( \Delta = \lambda_T / \gamma )\). Such enhanced local-field distribution might be related to the complex spatial arrangement of the Eu magnetic moments in EuAl\(_4\), where the magnetic propagation vector is incommensurate with the crystal lattice \[31\]. By contrast, in EuGa\(_4\), \( \lambda_T(T) \) follows the typical behavior of materials with a long-range (anti)ferromagnetic order \[36\], i.e., diverging at \( T_N \) and continuously decreasing at \( T < T_N \). Such \( \lambda_T(T) \) suggests a very homogeneous distribution of local fields, consistent with the commensurate magnetic propagation vector in EuGa\(_4\) \[32\]. At \( T = 1.5 \) K, in EuGa\(_4\), \( \lambda_T \) is found to be \( \approx 72 \mu\)s\(^{-1} \), a value which is almost three orders of magnitude smaller than that of EuAl\(_4\). This is also reflected in the ZF-\( \mu\)SR spectra shown in the insets of Fig. 3,
Table I. Summary of the EuAl₄ and EuGa₄ single-crystal parameters obtained by means of magnetization- and μSR measurements.

| Material | $T_N^L$ (K) | $T_N^{M1}$ (K) | $T_N^{M2}$ (K) | $B_{int}$ (T) | $\gamma$ | $\delta$ |
|----------|-------------|----------------|----------------|--------------|---------|---------|
| EuAl₄    | 15.6(2)     | 13.9(1)        | 16.0(2)        | 0.57(5)      | 2.50(5) | 0.50(5) |
| EuGa₄    | 12.3(3)     | —              | 13.7(4)        | 0.92(5)      | 0.17(3) |         |

| Material | $T_N^L$ (K) | $T_N^{M1}$ (K) | $B_{int}$ (T) | $\gamma$ | $\delta$ |
|----------|-------------|----------------|--------------|---------|---------|
| EuAl₄    | 16.5(2)     | 15.2(3)        | 16.5(4)      | 0.89(2) | 1.50(5) | 0.50(5) |

* Determined from the asymmetry of WfμSR spectra.
* Determined from fits of ZF-μSR spectra.

where the damping of the muon-spin precession is much weaker in EuGa₄ than in EuAl₄.

The longitudinal μSR relaxation rates $\lambda_\parallel$ shown in Fig. 4(c) and Fig. 5(c) are much smaller than the transverse relaxation rates $\lambda_\perp$. At 1.5 K, $\lambda_\parallel/\lambda_\perp \sim 0.15$ and 0.02 for EuAl₄ and EuGa₄, respectively. In contrast to $\lambda_\parallel(T)$ [see Fig. 4(b) and Fig. 5(b)], EuAl₄ and EuGa₄ exhibit a similar temperature-dependent $\lambda_\parallel(T)$, typical of materials with long-range magnetic order. In both cases, $\lambda_\parallel(T)$ diverges near $T_N$, followed by a significant drop at $T < T_N$, indicating that spin fluctuations are the strongest close to the onset of the AFM order. At 1.5 K, $\lambda_\parallel$ is 8.2 and 0.01 μs⁻¹ for EuAl₄ and EuGa₄, respectively. In EuAl₄, at temperatures well inside the AFM state, $\lambda_\parallel$ is hundreds of times larger than in EuGa₄, thus suggesting much stronger spin fluctuations in the AFM state of EuAl₄ than in EuGa₄. Conversely, in the PM state, both EuAl₄ and EuGa₄ exhibit similar $\lambda_\parallel$ values. Note that, in EuAl₄, as shown in Fig. 4(d), muons implanted in the second site experience only the spin fluctuations. Consequently, $\lambda_{int}(T)$ in EuAl₄ shows similar features to $\lambda_\parallel(T)$, i.e., it exhibits a maximum near the onset of the AFM order and it, too, decreases as the temperature is lowered. Future calculations of the muon-stopping sites, might be helpful to better appreciate the differences between EuAl₄ and EuGa₄.

In the fast-fluctuation limit (typical of magnetically ordered materials), the zero-field longitudinal muon-spin relaxation rate is described by:

$$\lambda_\parallel = \frac{2\gamma^2 E^2}{\nu},$$  \hspace{1cm} (5)

where $\Delta$ is the amplitude of field fluctuations, while $\nu$ is their correlation frequency (i.e., $1/\nu = \tau$, is the spin-correlation time) [34]. The estimated spin-correlation times are $\tau = 1.3$ and 8.2 ns for EuAl₄ and EuGa₄, respectively.

The vigorous spin fluctuations in these compounds are further supported by LF-μSR measurements. As shown in Fig. 6, the μSR spectrum in a 0.7-T longitudinal field is almost identical to that collected in a zero-field condition, suggesting that muon spins cannot be decoupled, hence, that spin fluctuations survive even in a field of 0.7 T in both EuAl₄ and EuGa₄. Note that, such spin fluctuations are robust against external magnetic fields, both in the AFM- (e.g., 1.5 K) and in the PM state (i.e., 50 K) far above $T_N$ (see details in Fig. 7 in the Appendix). Similar μSR results have been reported in other Eu-based materials, e.g., EuCd₂As₂, where the strong spin fluctuations cause the breaking of time-reversal symmetry and lead to the formation of magnetic Weyl fermions [38].

![FIG. 6.](image)

**C. Discussion**

First we discuss why the successive magnetic transitions of EuAl₄ remain undetected by μSR, an absence which might be due to different reasons. Firstly, the asymmetries obtained from WfμSR (see Figs. 1 and 2) reflect the internal fields sensed by the implanted muons. However, when the applied transverse field is much smaller than the internal fields, the WfμSR signal is mostly determined by the muons implanted in the residual NM (or PM) fraction of a magnetically ordered sample. This is reflected in a significant drop in the temperature-dependent asymmetry $A(T)$. In EuAl₄, below the onset of AFM order, the internal fields are hundreds of times larger than the applied WfμSR. Although changes in the magnetic structure, detected as successive transitions in the EuAl₄ magnetometry data, decrease the internal field from ~0.4 T to 0.33 T, this still remains much larger than WfμSR. Therefore, the successive magnetic transitions of EuAl₄ are not easily detectable via WfμSR measurements. Secondly, a slight change/arrangement of the magnetic structure does not have a large impact on the internal field. According to neutron scattering studies, in EuAl₄, the magnetic $g$-vector changes from $q_1 = (0.085, 0.085, 0)$ at $T_N = 13.5$ K to $q_2 = (0.170, 0, 0)$ at 11.5 K and slightly to $q_3 = (0.194, 0, 0)$ at 4.3 K [31]. Therefore, we identify the drop of $B_{int}$ at 13 K with the critical temperature where the magnetic structure changes from $q_1$ to $q_2$. At the same time, the modification of magnetic structure from $q_2$ to $q_3$ with the magnetic moments pointing at the same direction is too tiny to have a measurable effect on $B_{int}$. Thirdly, changes in magnetic structure have little effect on the longitudinal relaxation rates $\lambda_\parallel$, which reflect solely the spin fluctuations in EuAl₄. In general, spin fluctuations decrease significantly as the temperature moves away from $T_N$, but they diverge near the onset of the magnetic transition. Hence, in the magnetically ordered state, changes in $\lambda_\parallel$ caused by slight modifications of the magnetic structure are negligible compared to the temperature driven effects.

Since most of the skyrmion phases appear in a field range not easily accessible by standard μSR instruments, up to
now, only a handful of results have been reported where LF-µSR is used to study the skyrmion compounds. These include GaV_2(S,Se)_3 [39], Cu_2OSeO_3 [40], and the Co-Zn-Mn alloy [40, 41], whose skyrmion phases are stabilized by a relatively small field (< 0.1 T). While for many newly discovered skyrmion systems, i.e., GdRu_2Si_2 and Gd_3Ru_2Al_12 (as well as for EuAl and EuGaA studied here) [6, 7, 29, 30], the critical field required for stabilizing the skyrmion phase is above 1 T. In their AFM state, EuAl and EuGaA exhibit comparable spin fluctuations to other well-studied skyrmion compounds. For instance, the muon-spin relaxation rates extracted from LF-µSR measurements in the skyrmion phases of Cu_2OSeO_3 and GaV_2(S,Se)_3 are ∼ 0.2–0.8 µs⁻¹, similar to those of Eu(Al,Ga) (see Figs. 4 and 5). All these skyrmion compounds exhibit similar temperature-dependent muon-spin relaxation rates λ_1(T), with an enhanced and broadened peak in λ_1(T) at temperatures just below the critical temperature. Muon-spin relaxation rates also increase when entering the skyrmion phase by applying longitudinal magnetic fields, thus providing another method for identifying the presence of magnetic skyrmions. In the EuAl and EuGaA case, where there is no skyrmion phase in zero field, the relaxation rates diverge at T_N, followed by a significant drop at T < T_N due to the slowing down of spin fluctuations, a typical feature of magnetically ordered materials. A similar behavior is observed in CoO_0Zn_10 [40], a parent compound of the Co-Mn-Zn alloys, which lacks any skyrmion phases. According to Hall-resistivity measurements, the skyrmion phase may exist in a field range ~ 1–2.5 T in EuAl and ~ 4–7 T in EuGaA [6, 7]. Aimed at investigating the intrinsic magnetic properties of both compounds, most of the current µSR studies are performed in zero-field conditions. To compare the muon-spin relaxation rates of EuAl and EuGaA with those of other skyrmion compounds, and check if there are any skyrmion phases, further temperature-dependent µSR measurements under high magnetic fields are required.

The observation of a topological Hall effect in the magnetic state is usually attributed to noncoplanar spin textures, such as magnetic skyrmions, characterized by a finite scalar spin chirality in real space. These magnetic skyrmions are stabilized by the Dzyaloshinskii-Moriya interaction, often observed in noncentrosymmetric materials [42–48]. Conversely, magnetic materials with a centrosymmetric crystal structure that still host magnetic skyrmions are rare. To date, only a few systems have been reported, including some gadolinium intermetallic compound [19, 29, 30], Fe_3Sn_2 [49], and possibly also EuCd_2As_2 [50]. In centrosymmetric systems, skyrmions can be stabilized, for instance, by magnetic frustration (e.g., in GdRu_2Al_12, Gd_PdSi_2, and Fe_3Sn_2), or by the competition between the magnetic interactions and magnetic anisotropies (e.g., in GdRu_2Si_2) [19, 29, 30, 49, 51]. According to magnetization and nuclear magnetic resonance studies, the magnetic anisotropy is moderate in EuAl and EuGaA [6, 7, 52]. Since both EuAl and EuGaA adopt the same crystal structure of GdRu_2Si_2, skyrmions might be stabilized by the same mechanism. In addition, a four-spin interaction, mediated by itinerant electrons, has also been proposed as an important ingredient for the formation of skyrmions in centrosymmetric materials [51, 53, 54]. Very recently, the chiral magnet Co-Zn-Mn was found to host a skyrmion phase far below the magnetic ordering temperature, where spin fluctuations are believed to be the key for stabilizing the magnetic skyrmions [41]. Our µSR results reveal that both EuAl and EuGaA exhibit robust spin fluctuations against external magnetic fields, which analogously might be crucial for understanding the origin of topological Hall effect and of possible skyrmions in both materials.

IV. CONCLUSION

In summary, we investigated the temperature evolution of the local magnetic properties of EuAl and EuGa by means of µSR spectroscopy. wTF-µSR measurements confirm that EuAl and EuGa undergo an AFM transition at T_N ~ 16 and 16.5 K, which are consistent with the magnetization data. The magnetic volume fractions, as determined from wTF-µSR asymmetry, are 91% and 95% for EuAl and EuGa, respectively, implying a good sample quality in both cases. By using ZF-µSR measurements, we could follow the temperature evolution of the local magnetic fields and of spin fluctuations. The estimated internal fields at zero temperature are 0.33 and 0.89 T for EuAl and EuGa, respectively. EuAl exhibits a more disordered internal field distribution than EuGa, reflected in a large transverse muon-spin relaxation rate λ_T far below T_N, most likely related to its complex magnetic structure. The vigorous spin fluctuations revealed by both ZF-µSR and LF-µSR might be crucial for understanding the origin of topological Hall effect and of possible skyrmions in EuAl and EuGa. In future, it might be interesting to investigate the magnetic properties of EuAl and EuGa using the µSR technique under high magnetic fields, where the topological Hall effect appears.

ACKNOWLEDGMENTS

T.S. acknowledges support from the Natural Science Foundation of Shanghai (Grant Nos. 21ZR1420500 and 21JC1402300) and the Schweizerische Nationalfonds zur Förderung der Wissenschaftlichen Forschung (SNF) (Grant Nos. 200021_188706 and 206021_139082). Y.X. acknowledges support from the Shanghai Pujiang Program (Grant No. 21PJ1403100). This work was also financially supported by the Natural Science Foundation of China (NSFC) (Grant Nos. 12174103 and 11874150) and the Sino-Swiss Science and Technology Cooperation (Grant No. IZLCCZ-170075). We thank G. Lamura for the assistance during some phases of the LF-µSR experiments.

Appendix A: Longitudinal-field µSR in EuAl

In Fig. 7 we present the ZF- and LF-µSR spectra of EuAl, collected at temperatures well inside the AFM state (1.5 K) and far above T_N, in the PM state (i.e., 50 K). In the AFM state [see Fig. 7(a)], the fast drop of the µSR asymmetry reflects a very fast muon-spin depolarization in the first tenths of µs [see also ZF-µSR data in Fig. 3(a)]. A 0.78-T longitudinal magnetic field has negligible effects on the long-time µSR spectra. Indeed, both the ZF- and LF-µSR spectra are almost identical, implying that the spin fluctuations persist deep inside the AFM state of EuAl. Surprisingly, similar features are observed also in the PM state, as clearly demonstrated in Fig. 7(b) [see also Fig. 6]. Since the data suggest that muon spins cannot be decoupled neither in the AFM
nor in the PM state, this implies that, in this type of materials, spin fluctuations exist over a wide temperature range, well above the AFM transition. We recall that, according to previous μSR studies on EuCd₄As₂, spin fluctuations are strongly enhanced below 100 K, thus causing the breaking of time-reversal symmetry and leading to the formation of magnetic Weyl fermions [38]. Further measurements at higher temperatures, including both ZF- and LF-μSR, are highly desirable to check if a similar phenomenology occurs also in the BaAl₄-type family of materials.

**FIG. 7.** LF-μSR time-domain spectra collected at 1.5 K (a) (far below $T_N$) and 50 K (b) (far above $T_N$) in an applied magnetic field of 0 and 0.78 T in EuAl$_4$. Both spectra were collected in a longitudinal muon-spin configuration, i.e., $p_\mu \parallel S_\mu$. The applied magnetic field is parallel to the muon-spin direction.

- These authors contributed equally
- Corresponding authors: tshiroka@phys.ethz.ch
- Corresponding authors: tshang@phys.ecnu.edu.cn

[1] N. P. Armitage, E. J. Mele, and A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids, Rev. Mod. Phys. 90, 015001 (2018).

[2] B. Q. Lv, T. Qian, and H. Ding, Experimental perspective on three-dimensional topological semimetals, Rev. Mod. Phys. 93, 025002 (2021).

[3] K. Wang, R. Mori, Z. Wang, L. Wang, J. H. S. Ma, D. W. Latzke, D. E. Graf, J. D. Denlinger, D. Campbell, B. A. Bernevig, A. Lanzara, and J. Paglione, Crystalline symmetry-protected nontrivial topology in prototype compound BaAl₄, npj Quantum Mater. 6, 28 (2021).

[4] F. Kneidinger, L. Salmakaha, E. Bauer, I. Zeiringer, P. Rogl, C. Blaa-Schener, D. Reith, and R. Podloucky, Supercconductivity in noncentrosymmetric BaAl₄ derived structures, Phys. Rev. B 90, 024504 (2014).

[5] A. Nakamura, T. Uejo, H. Harima, S. Araki, T. C. Kobayashi, M. Nakashima, Y. Amako, M. Hedo, T. Nakama, and Y. Ōnuki, Characteristic Fermi surfaces and charge density wave in SrAl₄ and related compounds with the BaAl₄-type tetragonal structure, J. Alloys Compd. 654, 290 (2016).

[6] T. Shang, Y. Xu, D. J. Gawryluk, J. Z. Ma, T. Shiroka, M. Shi, and E. Pomjakushina, Anomalous Hall resistivity and possible topological Hall effect in the EuAl₄ antiferromagnet, Phys. Rev. B 103, 100204R (2021).

[7] H. Zhang, X. Y. Zhu, Y. Xu, D. J. Gawryluk, W. Xie, S. L. Ju, M. Shi, T. Shiroka, Q. F. Zhan, E. Pomjakushina, and T. Shang, Giant magnetoresistance and topological Hall effect in the EuGa₄ antiferromagnet, J. Phys.: Condens. Matter 33, 034005 (2021).

[8] S. Araki, Y. Ikeda, T. C. Kobayashi, A. Nakamura, Y. Hiranaka, M. Hedo, T. Nakama, and Y. Ōnuki, Charge density wave transition in EuAl₄, J. Phys. Soc. Jpn. 83, 015001 (2014).

[9] A. Nakamura, Y. Hiranaka, M. Hedo, T. Nakama, Y. Miura, H. Tsutsumi, A. Mori, K. Ishida, K. Mitamura, Y. Hirose, K. Sugiyama, F. Honda, T. Takeuchi, T. D. Matsuda, E. Yamamoto, Y. Haga, and Y. Ōnuki, Unique Fermi surface and emergence of charge density wave in EuGa₄ and EuAl₄, Jpn. Phys. Soc. Conf. Proc. 3, 011012 (2014).

[10] A. Nakamura, T. Uejo, F. Honda, T. Takeuchi, H. Harima, E. Yamamoto, Y. Haga, K. Matsubayashi, Y. Uwatoko, M. Hedo, T. Nakama, and Y. Ōnuki, Transport and magnetic properties of EuAl₄ and EuGa₄, J. Phys. Soc. Jpn. 84, 124711 (2015).

[11] S. Shimomura, H. Murao, S. Tsutsui, H. Nakao, A. Nakamura, M. Hedo, T. Nakama, and Y. Ōnuki, Lattice modulation and structural phase transition in the antiferromagnet EuAl₄, J. Phys. Soc. Jpn. 88, 014602 (2019).

[12] M. Kobata, S. Fujimori, Y. Takeda, T. Okane, Y. Saitoh, K. Kobayashi, Y. Yamagami, A. Nakamura, M. Hedo, T. Nakama, and Y. Ōnuki, Electronic structure of EuAl₄ studied by photoelectron spectroscopy, J. Phys. Soc. Jpn. 85, 094703 (2016).

[13] J. M. Moya, S. Lei, E. M. Clements, K. Allen, S. Chi, S. Sun, Q. Li, Y. Y. Peng, A. Husain, M. Mitrano, J. M. Kroogaard, R. Osborn, P. Abbamonte, A. B. Puthirath, J. W. Lynn, and E. Morosan, Incommensurate magnetic orders and possible field-induced skyrmions in the square-net centrosymmetric EuGa₄Al₄ system, arXiv: 2110.11925 (2021).

[14] Y. Tokura and N. Kanazawa, Magnetic skyrmion materials, Chem. Rev. 121, 2857 (2021), and references therein.

[15] A. Neubauer, C. Pfeifferer, B. Binz, A. Rosch, R. Ritz, P. G. Niklowitz, and P. Böni, Topological Hall effect in the $A$ phase of MnSi, Phys. Rev. Lett. 102, 186602 (2009).

[16] J. Gayles, F. Freimuth, T. Schena, G. Lani, P. Mavropoulos, R. A. Duine, S. Blügel, J. Sinova, and Y. Mokrousov, Dzyaloshinskii-Moriya interaction and Hall effects in the skyrmion phase of Mn$_{1-x}$Fe$_x$Ge, Phys. Rev. Lett. 115, 036602 (2015).

[17] N. Kanazawa, Y. Onose, T. Arima, D. Okuyama, K. Ohoyama, S. Wakimoto, K. Kakurai, S. Ishiwata, and Y. Tokura, Large topological Hall effect in a short-period helimagnet MnGe, Phys. Rev. Lett. 106, 156603 (2011).

[18] C. Franz, F. Freimuth, A. Bauer, C. Schnarr, C. Duvinage, T. Adams, S. Blügel, A. Rosch, Y. Mokrousov, and C. Pfeifferer, Real-space and reciprocal-space Berry phases in the Hall effect of Mn$_{1-x}$Fe$_x$, Phys. Rev. Lett. 112, 186601 (2014).

[19] T. Kurumaji, T. Nakajima, M. Hirschberger, A. Kikkawa, Y. Yasumasa, H. Sagayama, H. Nakao, Y. Taguchi, T.-H. Arima, and Y. Tokura, Skyrmion lattice with a giant topological Hall effect in a frustrated triangular-lattice magnet, Science 365, 914 (2019).
A. Fert, N. Reyren, and V. Cros, Magnetic skyrmions: Advances in physics and potential applications, Nat. Rev. Mater. 2, 17031 (2017).

M. Hirscher, T. Nakajima, S. Gao, L. Peng, A. Kikkawa, T. Kurumaji, M. Krienier, Y. Yamasaki, H. Sagayama, H. Nakao, K. Ohishi, K. Kakurai, Y. Taguchi, Y. Yu, T. Arima, and Y. Tokura, Skyrmion phase and competing magnetic orders on a breathing kagome lattice, Nat. Commun. 10, 5831 (2019).

N. D. Khanh, T. Nakajima, X. Yu, S. Gao, K. Shihata, M. Hirscher, Y. Yamasaki, H. Nakao, L. Peng, K. Nakajima, R. Takagi, T. Arima, Y. Tokura, and S. Seki, Nanometric square skyrmion lattice in a centrosymmetric tetragonal magnet, Nat. Nanotechnol. 15, 444 (2020).

K. Kaneko, T. Kawasaki, A. Nakamura, K. Munakata, A. Nakao, T. Hanashima, R. Kiyangani, T. Ohhara, M. Hedo, T. Nakama, and Y. Onuki, Charge-density-wave order and multiple magnetic transitions in divalent europium compound EuAl₃, J. Phys. Soc. Jpn. 90, 064704 (2021).

T. Kawasaki, K. Kaneko, A. Nakamura, N. Aso, M. Hedo, T. Nakama, T. Ohhara, R. Kiyangani, K. Oikawa, I. Tamura, A. Nakao, K. Munakata, T. Hanashima, and Y. Onuki, Magnetic structure of divalent europium compound EuGa₄ studied by single-crystal time-of-flight neutron diffraction, J. Phys. Soc. Jpn. 85, 114711 (2016).

A. A. Suter and B. M. Wojek, Munisift: A free platform-independent framework for μSR data analysis, Phys. Procedia 30, 69 (2012).

A. Younac and P. D. de Réotier, Muon Spin Rotation, Relaxation, and Resonance: Applications to Condensed Matter (Oxford University Press, Oxford, 2011).

M. Fujita, K. M. Suzuki, S. Asano, H. Okabe, A. Koda, R. Kadono, and I. Watanabe, Magnetic behavior of T-type Eu₂CoO₄ revealed by muon spin rotation and relaxation measurements, Phys. Rev. B 102, 045116 (2020).

L. M. Tran, M. Babij, L. Korosec, T. Shang, Z. Bukowski, and T. Shiroka, Magnetic phase diagram of Ca-substituted EuFe₂As₂, Phys. Rev. B 98, 104412 (2018).

Z. Guguchia, A. Shengelaya, A. Maisuradze, L. Howald, Z. Bukowski, M. Chikovani, H. Luetkens, S. Katrych, J. Karpinski, and H. Keller, Muon-spin rotation and magnetization studies of chemical and hydrostatic pressure effects in EuFe₂(As₁₋ₓPₓ), J. Supercond. Nov. Magn. 28, 285 (2015).

J.-Z. Ma, S. M. Nie, C. J. Yi, J. Jandke, T. Shang, M. Y. Yao, M. Naamneh, L. Q. Yan, Y. Sun, A. Chikina, V. N. Strocov, M. Medarde, M. Song, Y.-M. Xiong, G. Xu, W. Wulhhekel, J. Mesot, M. Reticicoli, C. Franchini, C. Mudry, M. Müller, Y. G. Shi, T. Qian, H. Ding, and M. Shi, Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of EuCd₅As₅, Sci. Adv. 5, eaaw4718 (2019).

K. J. A. Franke, B. M. Huddart, T. J. Hicken, F. Xiao, S. J. Blundell, F. L. Pratt, M. Crisanti, J. A. T. Barker, S. J. Clark, A. Stefancic, M. C. Hatnean, G. Balakrishnan, and T. Lancaster, Magnetic phases of skyrmion-hosting GaV₆S₈₋ₓSeₓ (y = 0, 2, 4, 8) probed with muon spectroscopy, Phys. Rev. B 98, 054428 (2018).

T. J. Hicken, M. N. Wilson, K. J. A. Franke, B. M. Huddart, Z. Hawkhead, M. Gomisalke, S. J. Clark, F. L. Pratt, A. Stefancic, A. E. Hall, M. Giomaga Hatnean, G. Balakrishnan, and T. Lancaster, Megahertz dynamics in skyrmion systems probed with muon-spin relaxation, Phys. Rev. B 103, 024428 (2021).

V. Ukleev, K. Karube, P. M. Derlet, C. N. Wang, H. Luetsken, D. Morikawa, A. Kikkawa, L. Margin-Thro, A. R. Wildes, Y. Yamasaki, Y. Yokoyama, L. Yu, C. Piamonteze, N. Jaouen, Y. Tokunaga, H. M. Rønnow, T. Arima, Y. Tokura, Y. Taguchi, and J. S. White, Frustration-driven magnetic fluctuations as the origin of the low-temperature skyrmion phase in Co₃Zn₃Mn₉, npj Quantum Mater. 6, 40 (2021).

S. Mülhüber, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, Skyrmion lattice in a chiral magnet, Science 323, 915 (2009).

X. Z. Yu, N. Kanazawa, Y. Onose, K. Kimoto, W. Z. Zhang, S. Ishiwata, Y. Matsu, and Y. Tokura, Near room-temperature formation of a skyrmion crystal in thin-films of the helimagnet Fe₃Ge, Nat. Mater. 10, 106 (2011).

X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa, and Y. Tokura, Real-space observation of a two-dimensional skyrmion crystal, Nature 465, 901 (2010).

S. Seki, X. Z. Yu, S. Ishiwata, and Y. Tokura, Observation of skyrmions in a multiferroic material, Science 336, 198 (2012).

I. Kézsmárkí, S. Bordacs, P. Milde, E. Neubler, L. M. Eng, J. S. White, H. M. Rønnow, C. D. Dewhurst, M. Mochizuki, K. Yanai, H. Nakamura, D. Ehlers, V. Tsurkan, and A. Loidl, Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV₆S₈, Nat. Mater. 14, 1116 (2015).

Y. Tokunaga, X. Z. Yu, J. S. White, H. M. Rønnow, D. Morikawa, Y. Taguchi, and Y. Tokura, A new class of chiral materials hosting magnetic skyrmions beyond room temperature, Nat. Commun. 6, 7638 (2015).

S. Seki, J.-H. Kim, D. S. Inosov, R. Georgii, S. Ishiwata, and Y. Tokura, Formation and rotation of skyrmion crystal in the chiral-latticeulator Cu₉O₄Se₃O, Phys. Rev. B 85, 220406(R) (2012).

H. Li, B. Ding, J. Chen, Z. Li, Z. Hou, E. Liu, H. Zhang, X. Xi, G. Wu, and W. Wang, Large topological Hall effect in a geometrically frustrated kagome magnet Fe₇Sn₂₀, Appl. Phys. Lett. 114, 192408 (2019).

Y. Xu, L. Das, J. Z. Ma, C. J. Yi, S. M. Nie, Y. G. Shi, A. Tiwari, S. S. Tsirkin, T. Neupert, M. Medarde, M. Shi, J. Chang, and T. Shang, Unconventional transverse transport above and below the magnetic transition temperature in Weyl semimetal EuCd₅As₅, Phys. Rev. Lett. 126, 076602 (2021).

C. D. Batista, S. Z. Lin, S. Hayami, and Y. Kamiya, Frustration and chiral orderings in correlated electron systems, Rep. Prog. Phys. 79, 084504 (2016).

H. Niki, S. Nakamura, N. Higa, H. Kuroshima, T. Toji, M. Yogi, A. Nakamura, M. Hedo, T. Nakama, Y. Onuki, and H. Harima, Studies of ⁷⁷Al NMR in Eu₃Al, J. Phys.: Conf. Ser. 592, 012030 (2015).
[53] S. Heinze, K. von Bergmann, M. Menzel, J. Brede, A. Kubetzka, R. Wiesendanger, G. Bihlmayer, and S. Blügel, Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions, Nat. Phys. 7, 713 (2011).
[54] R. Ozawa, S. Hayami, and Y. Motome, Zero-field skyrmions with a high topological number in itinerant magnets, Phys. Rev. Lett. 118, 147205 (2017).