

Field-tuning of ultrafast magnetization fluctuations in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$

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The properties of spin fluctuations in antiferromagnets are largely unexplored, in particular at ultrafast timescales. Here, we employ femtosecond noise correlation spectroscopy to experimentally study magnetization fluctuations in the canted antiferromagnet $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ across its spin-reorientation transition and under external magnetic fields. By comparing our measurements to atomistic spin noise and Monte Carlo simulations, we find that the amplitude of the spin noise is governed by the free energy, with stronger fluctuations in regions where the potential landscape softens. We furthermore demonstrate that external magnetic fields suppress spin fluctuations and enhance the quasiferromagnetic magnon frequency by effectively stiffening the potential. These results highlight an effective route for tuning ultrafast magnetization fluctuations via external parameters.

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I. INTRODUCTION

The development of high-speed, energy-efficient spintronic devices relies on materials that exhibit high-frequency and low-noise magnetization dynamics. Antiferromagnets (AFMs) are particularly promising in this regard due to their terahertz-range magnon frequencies, absence of stray fields, and resilience to external perturbations [1–4]. While much research has focused on the deterministic control of magnons in AFMs [5–7], their intrinsic spin fluctuation dynamics remain largely unexplored. Gaining insights into these fluctuations is crucial for designing a new generation of devices with minimized dissipation.

Recently, femtosecond noise correlation spectroscopy (FemNoC) [8–10] has emerged as a powerful technique for probing high-frequency spin fluctuations. By measuring correlations in polarization noise imprinted on pairs of consecutive femtosecond probe pulses via the Faraday effect, FemNoC provides direct access to the time-domain dynamics of magnon fluctuations.

In this work, we employ FemNoC to investigate the canted antiferromagnet $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$, focusing on the interplay between magnon fluctuations, the spin-reorientation transition (SRT), and the free-energy potential landscape. By systematically varying temperature and external magnetic field, we reveal how changes in the potential landscape dictate the fluctuation amplitude of the quasiferromagnetic (qF) magnon

mode. Our findings show that thermal fluctuations are enhanced in regions where the free-energy potential softens, a trend supported by atomistic spin noise and Monte Carlo simulations. Additionally, we demonstrate that an external magnetic field suppresses fluctuations and increases the qF magnon frequency by effectively stiffening the potential, offering a direct means of tuning ultrafast magnetization fluctuations via external control parameters.

II. METHODS

A. Experimental sample

The sample used in this study is a 10- μm -thick single crystal of the orthoferrite $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ [9–12] prepared via the floating zone technique [13–15]. In this material, Fe^{3+} electron spins are antiferromagnetically coupled, with a slight spin canting induced by the Dzyaloshinskii-Moriya interaction [16,17], resulting in a weak net ferromagnetic magnetization $\mathbf{M}$. Orthoferrites support two exchange modes at multi-THz frequencies and two magnon modes in the sub-THz regime: the quasiferromagnetic (qF) and quasi-antiferromagnetic (qAF) modes [18,19]. The qF mode corresponds to a precession of the weak ferromagnetic moment around its equilibrium axis, while the qAF mode involves longitudinal oscillations of this moment [9].

$\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ undergoes a temperature-induced spin-reorientation transition (SRT) near room temperature [9,11], where the magnetic anisotropy changes while the antiferromagnetic spin order remains intact. Within the SRT region ($T_L < T < T_U$), $\mathbf{M}$ continuously rotates from the crystallographic a axis (Γ_2 configuration) at the lower critical temperature T_L to the c axis at the upper critical temperature T_U (Γ_4 configuration) [20].

Phenomenologically, the $a - c$ plane spin reorientation of the net magnetization is understood in terms of the softening

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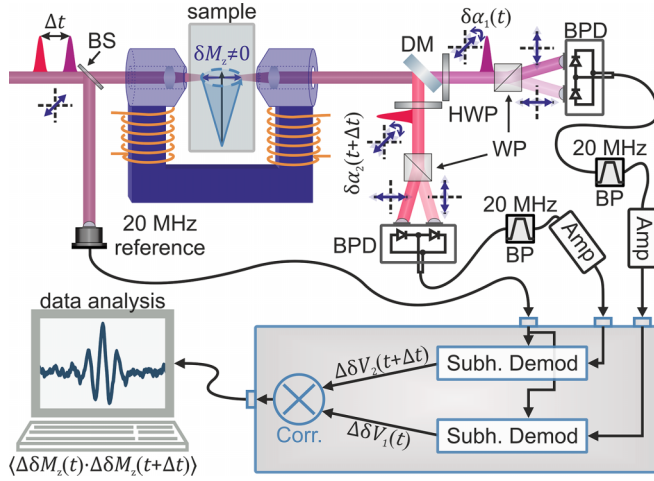


FIG. 1. Experimental setup and electronic data processing. The working principle is discussed in the main text. DM: dichroic mirror; HWP: half-wave plate; WP: Wollaston prism; BPD: balanced photodetector; BP: electronic bandpass filter; Amp: amplifier; Subh. Demod: subharmonic demodulation; Corr: real-time correlation.

of a Landau-type free energy [7,21–24],

$$F(\theta) = F_0 + K_2 \cos^2(\theta) + K_4 \cos^4(\theta) - \frac{1}{\mu_0} \mathbf{M} \cdot \mathbf{B}. \quad (1)$$

Here, θ is the angle between the net magnetization $\mathbf{M}$ and the a axis, F_0 is a constant free-energy term, K_2 and K_4 are the anisotropy constants of the second and fourth order, respectively, μ_0 is the vacuum permeability, and $\mathbf{B}$ is the external magnetic field. K_4 is approximately constant, whereas K_2 is assumed to be temperature dependent to account for the temperature-induced spin reorientation [21],

$$K_2(T) = 2K_4 \frac{T - T_U}{T_U - T_L}. \quad (2)$$

Minimization of Eq. (1) yields the real and stable solutions $\theta_1 = 0$, $\theta_2 = \frac{\pi}{2}$, and $\theta_3 = \arccos(\sqrt{-\frac{K_2}{2K_4}})$ for temperatures $T < T_L$, $T > T_U$, and $T_L < T < T_U$, respectively [21], thereby capturing the a -axis to c -axis SRT in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$.

Furthermore, the vanishing anisotropy difference between the a and c axes at T_L leads to an increased magnetic susceptibility in the $a-c$ plane [25] and significant softening of the qF mode resonance frequency [9,11,22,26–28]. This softening is accompanied by a strong enhancement of the qF magnon fluctuation amplitude and the emergence of picosecond stochastic switching [random telegraph noise (RTN)] [9].

B. FemNoC technique

In this work, we use femtosecond noise correlation spectroscopy [8–10,29,30] (FemNoC) to measure spontaneous magnetization fluctuations in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. A schematic of our experimental setup is shown in Fig. 1. FemNoC operates as follows: Two linearly polarized femtosecond laser pulse trains (40 MHz repetition rate) with slightly different center wavelengths (767 nm, purple; 775 nm red) and variable time delay Δt are focused through the magnetic sample with a transmissive objective lens (numerical aperture

$\text{NA} = 0.4$, working distance $\text{WD} = 3.9$ mm). The sample is positioned between the pole shoes of a custom-built electromagnet, which provides fields up to ± 450 mT along the laser propagation. The magnet design allows one to accommodate the objective lens within its inner structure and for the laser to transmit through its center, ensuring full compatibility with the optical setup.

Both probe pulse trains are polarized with the mean polarization angle $\langle \alpha_{1,2} \rangle = 45^\circ$ with respect to the optical table. Due to the Faraday effect, the light probes experience additional polarization rotations $\delta \alpha_1$ and $\delta \alpha_2$ that are proportional to the out-of-plane spin fluctuations δM_z . In our experiment, the laser propagation direction is aligned with the crystalline c axis of the sample, such that $\delta M_z = \delta M_c$. The polarization rotations $\delta \alpha_1$ and $\delta \alpha_2$ are measured in separate detection branches, each containing a half-wave plate (HWP), Wollaston prism (WP), and balanced photodetector (BPD). The WP splits the light into s - and p -polarized components (blue arrows), which the BPD converts into a voltage signal that is proportional to the optical power difference of the components. Consequently, if $\langle \alpha_{1,2} \rangle = 45^\circ$, the BPDs output a voltage that is proportional to the polarization fluctuations, $\delta \alpha_{1,2}$. The HWP is used to compensate for any static contributions to the Faraday rotation, e.g., induced by the static out-of-plane components of the net magnetization $\mathbf{M}$, and ensure $\langle \alpha_{1,2} \rangle \approx 45^\circ$. This balancing condition yields a zero output voltage from the BPDs, rendering the system highly sensitive to slight polarization changes that produce a measurable finite signal. As a result, the HWP angles under which the BPDs are balanced contain information about $\mathbf{M}$ and can be used to determine the angle θ between $\mathbf{M}$ and the crystalline a axis. This procedure is described in detail in Appendix C.

To evaluate the fluctuation part of the magnetization, the BPD output voltage is filtered with a bandpass, amplified and subharmonically demodulated [10,31] in a lock-in amplifier (UHFLI, Zurich Instruments) using the 20 MHz reference of the laser pulse train. The resulting pulse-to-pulse voltage fluctuations $\Delta \delta V_{1,2}$ are multiplied in real time and averaged over approximately 10^8 pulse pairs for each time delay Δt . This process yields the correlation trace of the out-of-plane magnetization dynamics, $\langle \Delta \delta M_x(t) \Delta \delta M_x(t + \Delta t) \rangle$. Further details on the experimental setup and data processing scheme can be found in Ref. [10].

C. Atomistic spin model simulations

Our experimental findings are compared with simulations of the spin noise around the SRT in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$, resting on an atomistic spin model and the stochastic Landau-Lifshitz-Gilbert equation [32–34]. $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ is modeled as a generic orthoferrite with magnetic moments on the Fe sites only. The extended Heisenberg Hamiltonian for the unity normalized spins $\mathbf{S}^i$ (on lattice site i) reads

$$H = - \sum_{i,j} \mathbf{S}^i \mathbf{J}^{ij} \mathbf{S}^j - \sum_i \mathbf{S}^i \kappa \mathbf{S}^i - \sum_i \sum_{\eta, v \in \{x, y, z\}} L_{\eta v} (S_\eta^i)^2 (S_v^i)^2 - \mu_S \mathbf{B} \sum_i \mathbf{S}^i. \quad (3)$$

The matrix J^{ij} in the first term includes the isotropic Heisenberg exchange, the Dzyaloshinskii-Moriya interaction, and a two-ion anisotropy, all taken into account up to the next-nearest neighbors. The second term is a second-order on-site anisotropy (also called single-ion anisotropy), competing with the aforementioned two-ion anisotropy, which leads to the SRT. The third term is a fourth-order on-site anisotropy, which determines the width of the SRT. The exact parameters can be found in Ref. [9]. The last term is the Zeeman term, with the magnetic field $\mathbf{B}$ and the amplitude of the spins $\mu_S = 3.66 \mu_B$.

The dynamics of the spins is governed by the Landau-Lifshitz-Gilbert equation,

$$\dot{\mathbf{S}}^i = -\frac{\gamma}{\mu_S(1+\alpha^2)} \mathbf{S}^i \times (\mathbf{H}^i + \alpha \mathbf{S}^i \times \mathbf{H}^i), \quad (4)$$

with the gyromagnetic γ , here set to the one of a free electron, and the Gilbert damping parameter $\alpha = 0.0002$. The effective field is given by

$$\mathbf{H}^i = -\frac{\partial H}{\partial \mathbf{S}^i} + \boldsymbol{\zeta}^i, \quad (5)$$

with a stochastic Gaussian white noise uncorrelated in space and time,

$$\begin{aligned} \langle \boldsymbol{\zeta}^i \rangle &= 0, \\ \langle \zeta_\eta^i(t) \zeta_\nu^j(t') \rangle &= \frac{2\alpha k_B T \mu_S}{\gamma} \delta_{ij} \delta_{\eta\nu} \delta(t - t'). \end{aligned} \quad (6)$$

The time evolution of a system of 192^3 spins is numerically calculated via the stochastic Heun's method.

D. Monte Carlo simulation

To phenomenologically model magnetization noise in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ within the SRT regime, we perform Monte Carlo (MC) simulations of a magnetization vector evolving in the temperature-dependent energy potential given by Eq. (1) for zero external field ($\mathbf{B} = 0$). Simulations are conducted in 0.1 K steps over the temperature range of 295–325 K, with critical SRT temperatures set at $T_L = 302$ K and $T_U = 322$ K.

For each simulated temperature value, an independent MC simulation is carried out. Each MC run begins with the magnetization at its equilibrium angle $\theta_{\min}(T)$, corresponding to the free-energy minimum. In cases where multiple degenerate minima exist, the minimum located within the quadrant $[0^\circ, 90^\circ]$ is selected as the initial state. The simulation proceeds for $n = 7000$ MC sweeps, with the magnetization undergoing random angular fluctuations $\delta\theta$ drawn from a uniform distribution in the range $[-3 \text{ rad}, +3 \text{ rad}]$.

The updated magnetization angle $\theta_{n+1} = \theta_n + \delta\theta$ is accepted if the Monte Carlo condition [35] is fulfilled, i.e., θ_{n+1} either reduces the free energy or

$$e\left(-\frac{(F_{n+1} - F_n)}{F_{\text{therm}}}\right) > x. \quad (7)$$

Here, x is a random variable drawn from a uniform distribution in $[0, 1]$. F_{therm} represents the thermal free energy. Note that because we will only regard normalized values of the free energy and simulated MC trajectories in this manuscript, F_{therm} is considered as a dimensionless constant.

III. RESULTS AND DISCUSSION

We perform FemNoC measurements on $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ across various out-of-plane magnetic fields and temperatures within the SRT region. T, two measurement approaches are employed:

(1) Temperature scan: The sample is held at a constant magnetic field while FemNoC measurements are taken at discrete temperatures ranging from 293 to 325 K. After completing each temperature scan, the sample is cooled back to 293 K to reset it to a reproducible magnetic state. Subsequently, the magnetic field is ramped to the next value within the range of -350 to $+350$ mT before initiating the next temperature scan sequence.

(2) Field scan: FemNoC and static magnetization measurements are performed at a fixed sample temperature while sweeping the external magnetic field from $+300$ to -300 mT and back. The temperature is then increased by 2 K prior to the next scan, covering a total temperature range from 296.15 to 308.15 K.

A. Temperature scan results

Figure 2(a) presents the FemNoC correlation waveforms recorded in temperature scans. These traces are symmetric around $\Delta t = 0$, characteristic of an autocorrelation function, with minor asymmetries attributed to background noise. The waveform shape exhibits strong dependence on temperature and external field; especially, a pronounced increase in the time-zero correlation amplitude (variance) is observed at higher temperatures. This increase is suppressed under applied magnetic fields.

Two distinct dynamical features are evident in the data: A damped picosecond oscillation around the zero-crossing line, present in all waveforms [see Fig. 2(a)]. This oscillation is identified as fluctuations of the quasiferromagnetic (qF) magnon mode [9,11]. An additional exponential decay lasting tens of picoseconds is detected at -1 mT for 300.15 and 303.15 K. This decay is indicative of picosecond spontaneous switching between two energetically degenerate quasi-equilibrium states [random telegraph noise (RTN)] [9]. These observations are reproduced in atomistic spin model simulations (Sec. II C), as shown in Fig. 2(b), which capture the temperature and field dependence of the noise variance and temporal dynamics.

In addition to fluctuation dynamics, our FemNoC setup also resolves the static out-of-plane magnetization component $\mathbf{M}$, allowing extraction of its angle θ relative to the crystalline a axis (Sec. II B). The temperature dependence of θ is shown in Fig. 3(a). For external fields below 60 mT and temperatures $T < 299$ K, $\theta \approx 0^\circ$ (i.e., $\mathbf{M} \parallel a$). Above 299 K, θ increases progressively, saturating at 90° for $T > 321$ K ($\mathbf{M} \parallel c$), characteristic of an SRT [36–38]. This finding allows us to identify the critical temperatures as $T_L \approx 299$ K and $T_U \approx 321$ K in the low-field regime.

For external fields exceeding 60 mT, θ deviates from zero even at the lowest temperatures, indicating a field-induced deflection of $\mathbf{M}$ towards the c axis. This shifts the SRT onset to lower temperatures, consistent with previous observations in ErFeO_3 [39]. Note that in a Landau-type free-energy descrip-

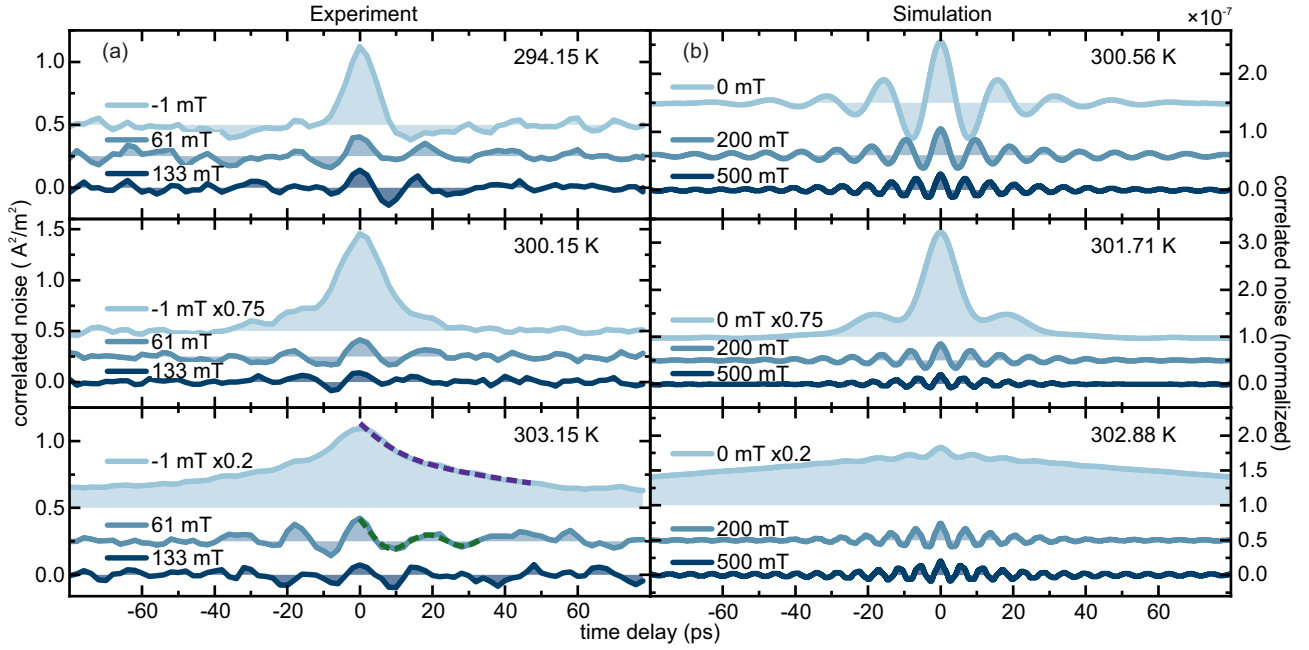


FIG. 2. Spin noise dynamics in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ as a function of probe-probe time delay Δt . (a) Experimental correlation time traces obtained from temperature scans in the range of 293 to 325 K and under various out-of-plane magnetic fields. Background subtraction was performed as described in Appendix A. The purple and green dotted lines are guide to the eyes, representing the exponential decay and damped picosecond oscillation around the zero-crossing line, corresponding to ultrafast random telegraph noise and quasiferromagnetic magnon noise, respectively. (b) Simulated noise correlation time traces for different magnetic fields along the crystalline c axis and temperatures within the SRT region. For clarity, both experimental and simulated waveforms are vertically shifted, with the shaded area indicating the zero line. Some traces additionally are scaled for better comparison.

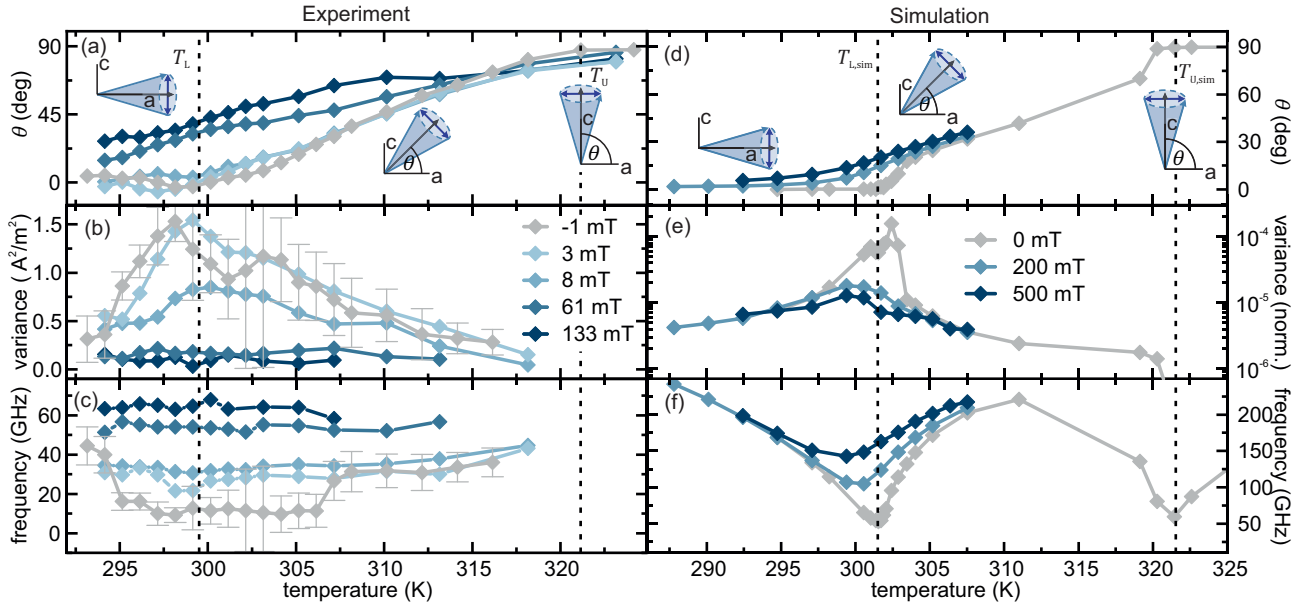


FIG. 3. Temperature dependence of c -axis component of the static magnetization and quasiferromagnetic (qF) magnon noise dynamics in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ under different c -axis magnetic fields. (a) Experimentally determined net magnetization angle θ as a function of temperature. The insets illustrate the net magnetization direction (black arrow) and transverse fluctuations (blue arrow) relative to the crystalline a and c axes. T_L and T_U denote the lower and upper critical temperatures of the spin-reorientation transition, respectively. (b), (c) Variance and center frequency of the experimentally measured qF magnon fluctuations as functions of temperature and c -axis magnetic field. (d) Simulated net magnetization angle θ as a function of temperature. (e), (f) Variance and center frequency of the simulated qF magnon fluctuations as functions of temperature and external magnetic field along the c axis. Note that the θ curves for $B = 3$ mT and $B = 61$ mT are taken from Ref. [12].

tion, the SRT consists of two second-order phase transitions at T_L and T_U , with order parameters $M_c = \cos(\theta)$ and $M_a = \sin(\theta)$, respectively. In this picture, the application of magnetic fields along the c axis breaks the symmetry (because now $M_c \neq 0$), suppressing critical phenomena at T_L and shifting T_U downward [24,40].

We now turn our discussion to the temperature dependence of the fluctuation dynamics. To investigate the individual dynamic features, we fit the correlated noise waveforms using

$$\langle M_z(t)M_z(t + \Delta t) \rangle = \sum_i A_i e^{-\frac{|\Delta t|}{\tau_i}} \cos(2\pi f_i \Delta t), \quad (8)$$

where $\langle M_z(t)M_z(t + \Delta t) \rangle$ are the correlated out-of-plane magnetization fluctuations as a function of the time delay Δt , A_i are the noise amplitudes (variances), τ_i are the damping constants, and f_i are the center frequencies. In the experiment, two fluctuation features—RTN and qF magnon noise—are observed, while simulations additionally resolve the quasi-antiferromagnetic (qAF) magnon mode [9]. Consequently, we fit experimental and simulated waveforms using $i = \{\text{RTN}, \text{qF}\}$ and $i = \{\text{RTN}, \text{qF}, \text{qAF}\}$, respectively (see Appendix A for fitting details). Note that for a two-level RTN process, the autocorrelation decays purely exponentially, yielding a Lorentzian power spectrum centered at zero frequency ($f_{\text{RTN}} = 0$) [41,42]. In contrast, in our data, the exponentially decaying component attributed to picosecond RTN exhibits a small but finite center frequency. We attribute this difference to the limited time window over which our traces are analyzed. This windowing artifact shifts spectral weight away from zero frequency and makes the RTN contribution appear as a weakly oscillatory (damped sinusoidal) component in the time domain, even though the underlying process remains RTN-like. To account for this, we do not set f_{RTN} to zero, but allow small but finite frequency values in the fitting process.

Figures 3(b) and 3(c) show the temperature dependence of the qF mode variance A_{qF} and resonance frequency f_{qF} . For fields below 60 mT, the qF mode variance exhibits a sharp enhancement near T_L , followed by a rapid decrease for higher temperatures. This observation is consistent with the magnetization rotation during the SRT [9]. Furthermore, this noise enhancement is accompanied by a softening of the qF mode resonance frequency f_{qF} . Note that RTN, with frequencies comparable to f_{qF} , emerges in the same temperature range as the qF mode softening. This increases the uncertainty in both qF mode variance and frequency estimations [error bars in Figs. 3(b) and 3(c)]. Appendix B discusses the uncertainty analysis in detail.

Both the variance enhancement and frequency softening are most pronounced at $B = -1$ mT and diminish as the field increases. For $B > 60$ mT, these effects vanish, indicating field-induced suppression of the critical behavior at T_L . This aligns with the expectation that critical fluctuations at a second-order phase transition weaken as external fields modify the free-energy landscape. To our knowledge, the frequency evolution of the qF mode in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ as a function of both temperature and magnetic field strength has not been reported to date. The zero-field results reported in [11] are consistent with our results, as discussed in [9].

All these experimental trends are reproduced in atomistic spin dynamics simulations. The net magnetization rotates from $\theta = 0^\circ$ to $\theta = 90^\circ$, initiating at $T_{L,\text{sim}} \approx 302$ K and concluding at $T_{U,\text{sim}} \approx 322$ K [Fig. 3(d)]. The simulated qF mode variance and resonance frequency [Figs. 3(e) and 3(f)] exhibit similar temperature-dependent behavior, including variance enhancement at $T_{L,\text{sim}}$ and mode softening at both $T_{L,\text{sim}}$ and $T_{U,\text{sim}}$. It should be noted that due to the complexity of the model, it is difficult to find a single set of spin model parameters that reproduces all experimental observables simultaneously, such as the Néel temperature, reorientation temperatures, and eigenfrequencies. Moreover, some effects present in the experiment, including domain structure and crystal defects, are not included in the simulations. These limitations account for the quantitative discrepancies between the simulated and measured SRT range and qF mode frequency, including its temperature dependence. The complete analysis of the atomistic spin noise simulation results, including temperature dependence of the qAF mode and RTN is given in Appendix D.

Note that our FemNoC experiment is only sensitive to fluctuations along the laser propagation direction, which in our setup is aligned with the crystalline c axis. Therefore, we cannot directly resolve qF mode fluctuations near T_U because these take place along the crystalline a axis.

Applying a magnetic field suppresses both variance enhancement and mode softening, albeit less strongly in simulations than in experiments. The discrepancy likely stems from both the practical limitations in fine-tuning simulation parameters to match experimental details of the reorientation transition (see Sec. II C) and the effect of the external magnetic field on the order parameter. As Figs. 3(a) and 3(d) show, in the experiment, the rotation angle around T_L is clearly more affected by the external field than in the simulation and the temperature range of the reorientation transition is broadened. Consequently, critical features remain more pronounced in the simulation data. Nonetheless, the overall temperature and field dependence of the qF mode variance and resonance frequency show excellent qualitative agreement between experiment and simulation.

B. Comparison to Monte Carlo simulation

We now investigate the dependence of thermal fluctuations on the free-energy landscape using phenomenological Monte Carlo (MC) simulations. The free energy is computed at multiple temperatures across the SRT, following Eq. (1). At each temperature, we perform a MC simulation of a magnetization vector subjected to random angular fluctuations within the corresponding potential. Further details on the MC simulations can be found in Sec. II D. The computed free energies along with simulated MC trajectories are shown in Fig. 4(a).

Below $T_{L,\text{sim}}$, the free energy exhibits a dumbbell shape with minima at $\theta = 0^\circ$ and $\theta = 180^\circ$, indicating that the magnetization easy axis lies along the crystalline a axis. This results in two possible domain configurations with magnetization pointing along either the positive or negative a direction. In this regime, the MC trajectory remains confined to a narrow range around the energy minimum.

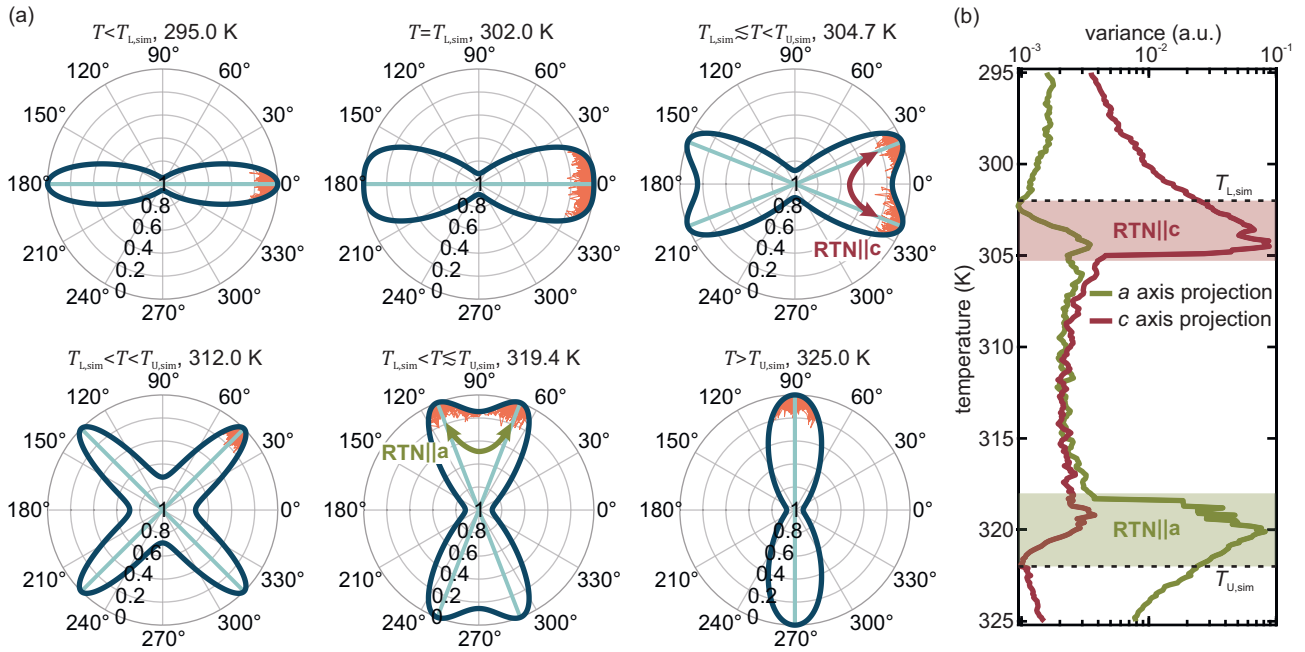


FIG. 4. Monte Carlo simulated magnetization noise across the SRT region in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. (a) Normalized free energy (dark blue) and Monte Carlo simulated net magnetization trajectories (orange) as functions of net magnetization angle θ and temperature. Light blue lines mark the easy-axis directions where the free energy is minimized. (b) Variances of the net magnetization projections along the a axis (green) and c axis (red) as a function of temperature. Green and red shaded regions indicate temperature ranges where random telegraph noise (RTN) occurs in the Monte Carlo simulation.

At $T = T_{L,\text{sim}}$, the free-energy landscape softens, characterized by a broadening of the potential well. As a result, the MC trajectory explores a wider range of angles. During the SRT ($T_{L,\text{sim}} < T < T_{U,\text{sim}}$), the easy axis splits into two branches, rotating in opposite directions as the transition progresses. In this regime, the magnetization can occupy four distinct domain configurations corresponding to the degenerate free-energy minima [24,43]. Near $T_{L,\text{sim}}$ (e.g., 304.7 K), the energy barrier separating adjacent minima is small compared to the thermal energy, allowing for spontaneous switching between these states. Note that the RTN magnitude in the MC simulation appears significantly larger than observed in FemNoC experiments [12], which is a consequence of the chosen simulation parameters.

At higher temperatures (e.g., 312 K), the energy barriers become too large to be overcome. As a result, fluctuations remain confined to the local minimum in which the Monte Carlo simulation is initialized. As $T_{U,\text{sim}}$ is approached, the two easy axes converge toward the c -axis direction. Just below $T_{U,\text{sim}}$, the energy barrier between adjacent minima becomes small enough to permit RTN along the crystalline a axis. For $T > T_U$, the two easy axes merge, forming new free-energy minima at 90° and 270° (easy axis now parallel to c axis), completing the spin-reorientation transition.

Figure 4(b) shows the variance of the MC trajectories projected along the a axis and c axis. The c -axis variance exhibits a pronounced enhancement near $T_{L,\text{sim}}$, attributed to the softening of the free-energy potential. At higher temperatures, the emergence of RTN further amplifies the noise, before eventually vanishing as the SRT progresses, leading to a significant decrease in variance. The a -axis variance follows a similar but inverted trend, with a pronounced enhancement

near $T_{U,\text{sim}}$. These findings closely align with both experimental observations and atomistic simulations, suggesting that the experimentally observed trends can be understood as a direct consequence of the temperature-dependent free-energy landscape. This further implies that FemNoC enables direct mapping of the magnetization potential landscape.

C. Field scan results

The results of the field scan are presented in Fig. 5. Figure 5(a) shows the net magnetization angle θ as a function of magnetic field. The data reveal clear hysteretic behavior between the up and down sweeps, which varies with temperatures in both saturation angle and steepness. This hysteresis suggests the formation of magnetic domains within the corresponding field range [43].

At $T = 308.15$ K, the field loop exhibits a rectangular shape characteristic of an easy-axis magnetization loop. As the temperature decreases, the loop progressively adopts a hard-axis-like shape. This trend aligns with the known SRT in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$, where the easy axis rotates from $\mathbf{M}||a$ at $T < T_L$ to $\mathbf{M}||c$ at $T > T_U$ (see Fig. 4). Consequently, the expected field loop behavior transitions from easy-axis-like to hard-axis-like as temperature increases [43], in agreement with our observations.

Interestingly, no hysteresis is expected when the external field is applied along the hard axis [43], which should be the case for $T < T_L$ (see Fig. 4). Nevertheless, our lowest recorded temperature (296.15 K) still shows a significant hysteretic effect, despite being below T_L as identified in the temperature scan. This discrepancy is likely due to a slight sample misalignment, such that the external magnetic field

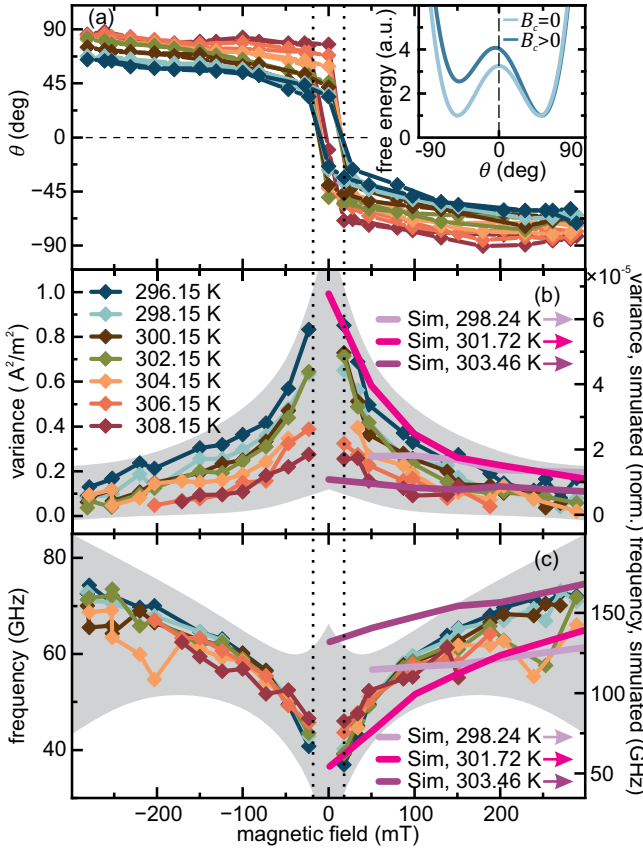


FIG. 5. Field dependence of the experimentally determined and simulated c -axis component of static magnetization and quasiferromagnetic (qF) magnon noise dynamics in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. (a) Experimentally determined net magnetization angle θ as a function of the external field. Inset: Free energy calculated from Eq. (1) as a function of θ without (light blue curve) and with (dark blue curve) external magnetic field along the crystalline c axis in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ held at $T = 305$ K. (b),(c) Variance and center frequency of the qF magnon fluctuations as a function of the external magnetic field along the crystalline c axis. The gray shaded area represents the uncertainty of the extracted values, while the dotted vertical lines mark the field range where pronounced random telegraph noise occurs. RTN leads to increased uncertainty, which is why we omit the data in this region. Details on the uncertainty evaluation are provided in Appendix B.

is not perfectly parallel to the crystalline easy axis (a axis), leading to finite hysteretic effects.

The inset of Fig. 5(a) illustrates the change in the free-energy potential of $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ under an external magnetic field applied along the crystalline c axis. At $B_c = 0$, the system exhibits two degenerate minima at $\pm 45^\circ$. The application of a field $B_c > 0$ lifts this degeneracy, rendering the local minimum at -45° energetically less favorable, while the global minimum at $+45^\circ$ is stabilized and stiffened. This behavior reflects a field-induced bias in the domain population: domains with magnetization components parallel to the external field are energetically favored, whereas those with antiparallel components are suppressed, consistent with the observed hysteresis curves.

Figure 5(b) shows the c -axis qF mode variance as a function of magnetic field along the c direction at different

temperatures. The noise amplitude systematically decreases with increasing field, coinciding with a characteristic increase in the qF mode frequency [Fig. 5(c)]. Due to a significant enhancement of RTN in the field range of -22 to $+17$ mT, we omitted data points in this interval [see Appendix B, Fig. 8(b)]. Both the variance reduction and frequency enhancement with increasing external field are qualitatively reproduced by the atomistic spin noise simulations [purple curves in Figs. 5(b) and 5(c)]. As in the experiment, both effects are temperature dependent, being most pronounced around the critical temperature ($T_{L,\text{sim}} \approx 301.7$ K) and gradually diminishing when the temperature is farther away from $T_{L,\text{sim}}$. This can be understood by noting that away from the critical temperature, the potential is already stiffened by thermal effects, so an external magnetic field produces only a minor relative change in the fluctuation dynamics. Furthermore, changes in temperature and magnetic field alter the equilibrium angle θ , which in turn modifies the c -axis component of the qF mode fluctuations.

To isolate the contribution of θ , we computed the absolute transverse magnetization noise $|\delta \mathbf{M}|$ in the $a - c$ -plane from the c -axis projection δM_c , using the trigonometric relationship

$$|\delta \mathbf{M}| = \frac{\delta M_c}{\cos(\theta)}. \quad (9)$$

The total magnetization fluctuation $|\delta \mathbf{M}|$ as a function of magnetic field is shown in Fig. 6(a). Note that the 306.15 and 308.15 K measurements are omitted here, due to the high uncertainty associated with the small noise amplitude. Even after correcting for the SRT, a negative trend remains, indicating a suppression of spin fluctuations with increasing field. Simultaneously, the relationship between noise variance and qF mode frequency persists, as shown in Fig. 6(b). This further corroborates the notion: A magnetic field applied along the easy axis stiffens the free-energy potential [see inset of Fig. 5(a)], reducing spin fluctuations, while increasing the qF mode frequency.

IV. CONCLUSION

We investigated ultrafast magnetization fluctuations in the antiferromagnet $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ using femtosecond noise correlation spectroscopy (FemNoC). By systematically varying temperature across the spin-reorientation transition and applying external magnetic fields, we explored the relationship between spin fluctuations, the free-energy landscape, and quasiferromagnetic (qF) magnon properties.

Our findings show that the magnitude of spin fluctuations at picosecond timescales is dictated by the free-energy potential, with fluctuations increasing in regions where the energy landscape softens. Monte Carlo and atomistic spin noise simulations confirm this trend, highlighting a direct correlation between fluctuation amplitude and variations in the free-energy curvature. Furthermore, we demonstrate that an external magnetic field suppresses spin fluctuations while increasing the qF magnon frequency, an effect attributed to field-induced stiffening of the free-energy potential. These trends are consistently observed in both experiment and simulation.

Overall, our results provide insight into the tunability of ultrafast spin fluctuations through external fields, which is

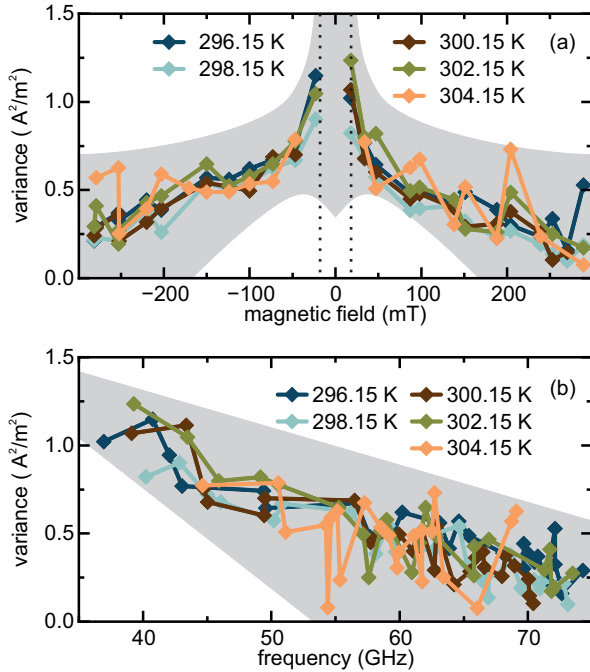


FIG. 6. Field and frequency dependence of the SRT compensated quasiferromagnetic (qF) magnon noise variance in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. (a) Total qF mode variance as a function of the external magnetic field along the crystalline c axis. (b) Total qF mode variance as a function of the qF mode resonance frequency. The gray shaded area represents the uncertainty of the extracted values, while the dotted vertical lines mark the field range where pronounced random telegraph noise occurs. RTN leads to increased uncertainty, which is why we omit the data in this region. Details on the uncertainty evaluation are provided in Appendix B.

relevant for the development of high-frequency, low-noise spintronic devices. Additionally, they underscore the potential of FemNoC as a tool to characterize magnetization potentials in complex magnetic systems.

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The authors declare no competing interests.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain sensitive personal

information. The data are available from the authors upon reasonable request.

APPENDIX A: POSTPROCESSING AND ANALYSIS OF EXPERIMENTAL DATA

The experimental data presented in this manuscript are subject to several postprocessing and analysis steps. First, background correlations are eliminated using a linear subtraction procedure. Here, we define the background as a linear function connecting the average values of the first and last 20 ps of the respective correlation waveform. In the next step, this background function is linearly subtracted from the raw data. Note that the correlation of random telegraph noise (RTN) is an exponentially decaying function, with the exponential being proportional to the mean dwell time of the RTN process [9]. Consequently, the exponential decay does not settle to zero within our measurement time window for slow RTN processes (long dwell times). To retain this finite y-axis offset and avoid artifacts from the linear background subtraction, all correlation waveforms showing significant RTN contributions [e.g., Fig. 7(b)] are subtracted by the average background of all other waveforms.

To express our FemNoC data in absolute magnetization units of $(\text{A}/\text{m})^2$, we calibrate the waveforms using the protocols described in Ref. [12]. The calibration factors used in this manuscript must be adjusted according to the optical probe powers employed during the measurements. Specifically, the raw data for the temperature scans (Figs. 2 and 3) and field scans (Figs. 5 and 6) were acquired at optical powers of 0.95 and 1.09 mW per probe beam, respectively. This results in calibration factors of $8.7 \frac{\mu\text{V}}{(\text{A}/\text{m})^2}$ and $11.4 \frac{\mu\text{V}}{(\text{A}/\text{m})^2}$, respectively, which scale quadratically with optical power, as detailed in Ref. [12]. The raw voltage data from the temperature and field scans are divided by these calibration factors to yield the correlated noise in units of $(\text{A}/\text{m})^2$. For details on the uncertainty analysis of the calibration procedure, please refer to Ref. [12]. Representative calibrated correlation waveforms are shown in Figs. 2 and 7.

Analysis of the correlated noise of both experimental and simulated correlation waveforms is performed with the fitting function given in Eq. (8). Examples of the time-domain fitting of experimental data and the corresponding Fourier spectra of data and fits are shown in Fig. 7.

Note that when the qF mode and RTN noise features show finite overlap in the frequency domain, their amplitudes, damping, and frequencies can no longer be unambiguously attributed to a single source. This effect needs to be considered in the analysis, and corresponding uncertainties must be attributed to the fitting parameters. This is further discussed in Appendix B.

APPENDIX B: UNCERTAINTY EVALUATION OF EXPERIMENTAL PARAMETERS

The experimental values presented in Figs. 3, 5, and 6 exhibit finite uncertainties, primarily due to limited signal strength and the time-domain fitting procedure (see Appendix A). The latter effect becomes particularly relevant when the individual noise features exhibit spectral overlap, such as

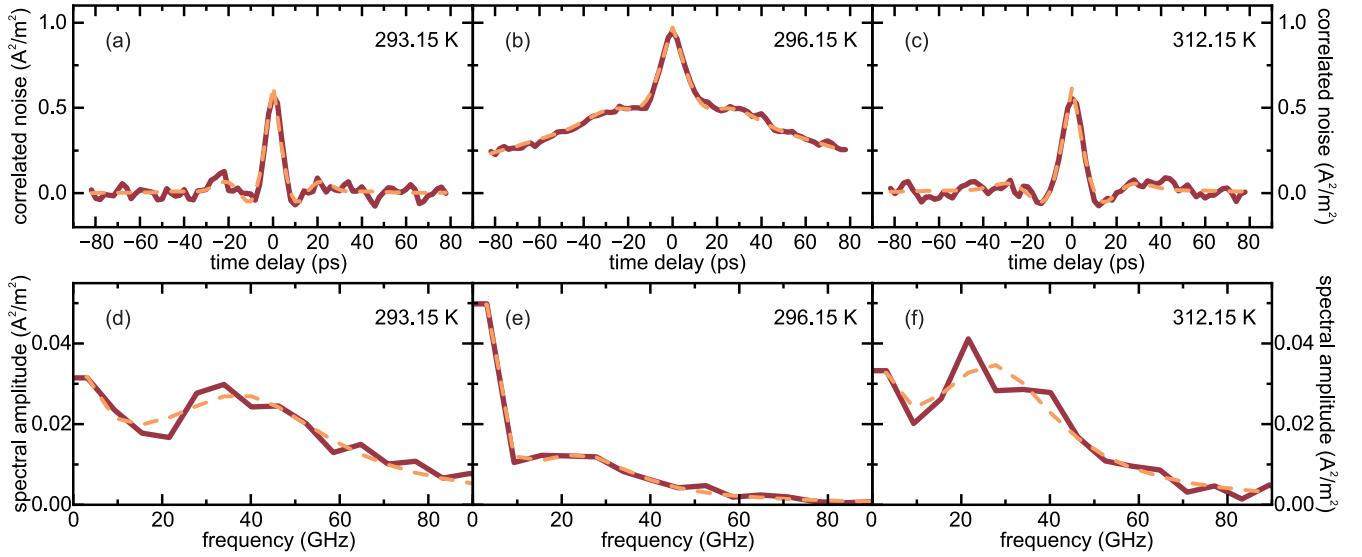


FIG. 7. Example of parameter extraction via time-domain fitting of the measured correlation time traces. (a)–(c) Correlation time traces (red) recorded for the $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ sample held at an external out-of-plane magnetic field of 5 mT and time-domain fits (orange) using the fitting function $\langle M_c(0)M_c(\Delta t) \rangle = A_{\text{RTN}} e^{-\frac{|\Delta t|}{\tau_{\text{RTN}}}} \cos(2\pi f_1 \Delta t) + A_{\text{qF}} e^{-\frac{|\Delta t|}{\tau_{\text{qF}}}} \cos(2\pi f_{\text{qF}} \Delta t)$. (d)–(f) Corresponding frequency spectra of the measured correlation time traces (red) and time-domain fits (orange).

when RTN is comparable in magnitude to the magnon noise. To account for these effects, we estimate the uncertainties of our data using a combination of absolute, relative, and RTN amplitude-dependent contributions. The resulting uncertainty functions are summarized in Table I. Figure 8(a) presents the frequencies and variances of the qF magnon fluctuations obtained from the field scan (Fig. 5), along with their calculated uncertainties. The corresponding RTN variances are shown in Fig. 8(b).

As discussed in the main text, applying an external magnetic field alters the potential landscape, leading to a strong reduction in qF mode variances. This decrease in the signal-to-noise ratio increases the uncertainty in the qF mode frequency f_{qF} . Conversely, at low external fields, the qF magnon noise

is enhanced, coinciding with the emergence of RTN at similar frequencies [Figs. 7(b) and 7(e)]. The resulting spectral overlap significantly increases the uncertainty in both A_{qF} and f_{qF} . Consequently, we exclude data points from the field scan results for small external fields ($B \in [-22 \text{ mT}, +17 \text{ mT}]$). The same uncertainty analysis is applied to the temperature scan data presented in Fig. 3.

APPENDIX C: EVALUATION OF THE NET MAGNETIZATION ANGLE

As discussed in Sec. II B, our FemNoC setup also allows us to measure the net magnetization angle θ relative to the crystallographic a axis (in-plane direction) of $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$.

TABLE I. Definition of uncertainty functions u corresponding to the fitting parameters extracted from experimental correlation wave functions. A_{RTN} and A_{qF} : variances of random telegraph noise and qF mode. f_{mqF} : frequency of qF mode. $S = 0.05 \left(\frac{\text{Å}}{\text{m}}\right)^2$: Magnetization sensitivity of the experimental setup estimated from the background noise.

Fit parameter	Uncertainty function
A_{RTN}	$u(A_{\text{RTN}}) = \underbrace{\frac{S}{\text{absolute error}}}_{\text{(sensitivity)}} + \underbrace{\frac{0.3 \cdot A_{\text{RTN}}}{\text{relative error}}}_{\text{(fit accuracy)}} + \underbrace{0.1 \left(\frac{\text{Å}}{\text{m}}\right)^2}_{\text{absolute error (dc offset)}}$
A_{qF}	$u(A_{\text{qF}}) = \underbrace{\frac{S}{\text{absolute error}}}_{\text{(sensitivity)}} + \underbrace{\frac{0.1 \cdot A_{\text{qF}}}{\text{relative error}}}_{\text{(fit accuracy)}} + \underbrace{\frac{0.5 \cdot A_{\text{RTN}}}{\text{RTN amp. dependent error}}}_{\text{RTN amp. dependent error}}$
f_{qF}	$u(f_{\text{qF}}) = \underbrace{\frac{3 \text{ GHz}}{\text{absolute error}}}_{\text{absolute error}} + \underbrace{\frac{0.05 \cdot f_{\text{qF}}}{\text{relative error}}}_{\text{(fit accuracy)}} + \underbrace{\frac{8 \text{ GHz} \cdot \frac{S}{A_{\text{qF}}}}{\text{qF amp. dependent err.}}}_{\text{qF amp. dependent err.}} + \underbrace{\frac{0.5 \text{ GHz} \cdot \frac{A_{\text{RTN}}}{S}}{\text{RTN dependent err.}}}_{\text{RTN dependent err.}}$

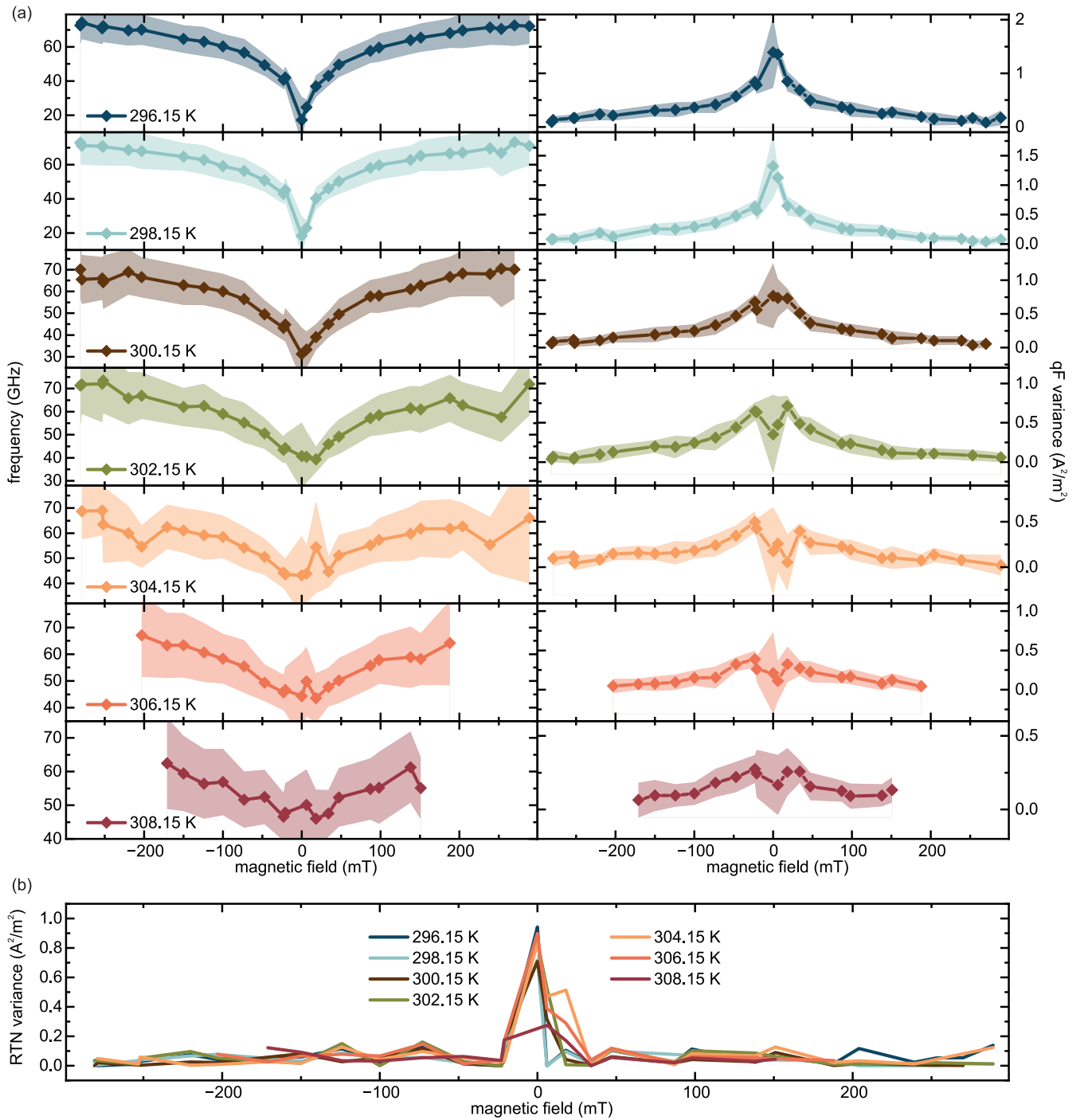


FIG. 8. Fitting parameters and corresponding uncertainties obtained from the field scan. (a) Frequency and variances of the qF magnon fluctuations for different sample temperatures as a function of external magnetic field in the out-of-plane direction. (b) RTN variances for different sample temperatures as a function of external magnetic field in the out-of-plane direction.

This is achieved by determining the half-wave plate angles at which the BPDs are balanced. This is the case when incident light on the Wollaston prisms is polarized at 45° relative to their optical axes. Below the lower threshold temperature of the spin-reorientation transition T_L , the sample's net magnetization lies along the a axis, meaning no static magnetization component exists along the laser's propagation direction. Above T_L , the magnetization rotates by an angle

$\theta(T)$ towards the c axis, acquiring a finite out-of-plane component. This component induces a static Faraday rotation in the optical probes, which must be compensated by adjusting the half-wave plates before each FemNoC measurement. Consequently, the half-wave plate angles encode information about θ .

Figure 9(a) displays the absolute half-wave plate angles as a function of sample temperature under different

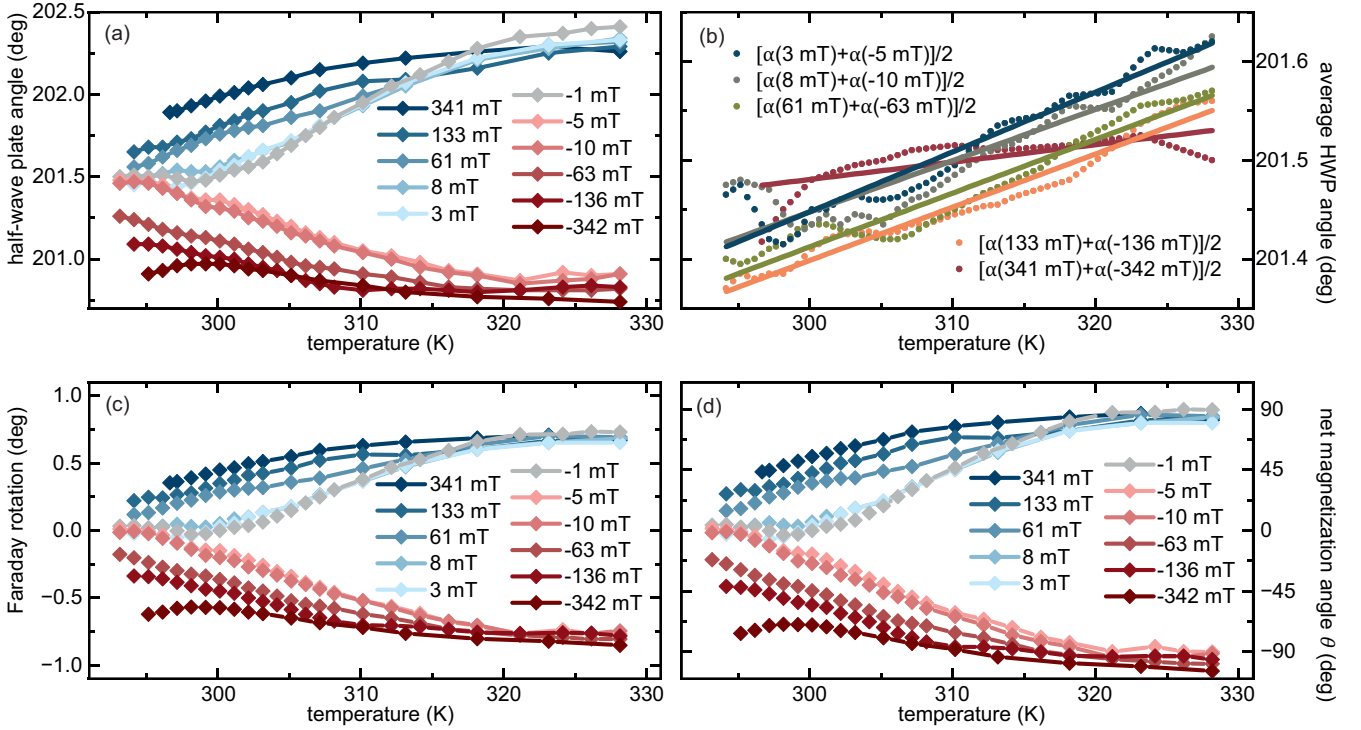


FIG. 9. Evaluation of the net magnetization angle at different temperatures and external magnetic fields in the sample out-of-plane direction. (a) Half-wave plate angle (raw data) as a function of temperature. (b) Interpolated average half-wave plate (HWP) angle of field pairs of similar absolute magnitude as a function of temperature (dotted lines) and linear fits (solid lines). (c) Offset and asymmetric background corrected Faraday rotation as a function of temperature. (d) Temperature dependence of the angle θ between net magnetization and crystalline a axis in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. Note that the θ curves for $B = -63, -5, 3$, and 61 mT are taken from Ref. [12].

out-of-plane magnetic fields. These angles vary significantly with sample temperature and external magnetic field due to the spin-reorientation transition. Notably, slight discrepancies appear between measurements performed at positive and negative fields of similar magnitude. This effect may be explained by temperature-dependent birefringence of the sample, which introduces an additional polarization rotation component that is independent of the sample's magnetization [12,44].

To isolate this asymmetric background, we interpolate the data in Fig. 9(a) and sum two half-wave plate curves measured at positive and negative fields of similar magnitude. Figure 9(b) presents the results, where linear fits reveal the asymmetric backgrounds. After subtracting the backgrounds from the raw data [Fig. 9(a)], we define the zero-reference level as the average of the values recorded below 297 K for fields $|B| < 15$ mT. The resulting relative Faraday rotation is shown in Fig. 9(c).

For temperatures $T > T_U = 321$ K, the Faraday rotation curves stabilize at comparable relative values. Assuming $\theta(T > T_U) = \pm 90^\circ$, we normalize the Faraday rotation data using the maximum (minimum) values of the -1 mT (-5 mT) curves, along with the previously established zero reference. The extracted net magnetization angles $\theta(T)$ are shown in Fig. 9(d) and, for positive fields only, in Fig. 3(c). The same reference levels are applied to half-wave plate angles from the field scan, yielding the θ reference levels obtained in this procedure are also applied to the half-wave plate angles

measured in the field scans, resulting in the net magnetization curves shown in Fig. 5(c).

APPENDIX D: FULL ANALYSIS OF SIMULATION DATA

Figure 10 represents the complete results of the atomistic simulations. The temperature dependence of the qF and qAF magnon frequencies is shown in Fig. 10(a). The qF mode exhibits characteristic softening near the critical temperatures, an effect that is suppressed under applied magnetic fields. On the contrary, the qAF mode frequency remains largely temperature independent, with only a slight field-induced increase.

Figure 10(b) displays the qF mode variance temperature dependence for different axis projections. The c -axis projection initially increases around T_L , reflecting the softening of the free-energy potential, before decreasing due to the SRT. Simultaneously, the a -axis projection steadily rises, peaking near T_U . This noise enhancement is significantly reduced by external magnetic fields, which introduces stiffening of the magnetic potential. In contrast, the b -axis projection remains largely unchanged throughout the SRT, suggesting a stable free-energy landscape along this direction.

The fluctuation amplitude of the qAF is shown in Fig. 10(c). While the latter also exhibits an increase near the critical temperatures, this effect is much weaker than for the qF mode. Interestingly, external fields have little impact on the qAF mode noise increase near $T_{L,\text{sim}}$.

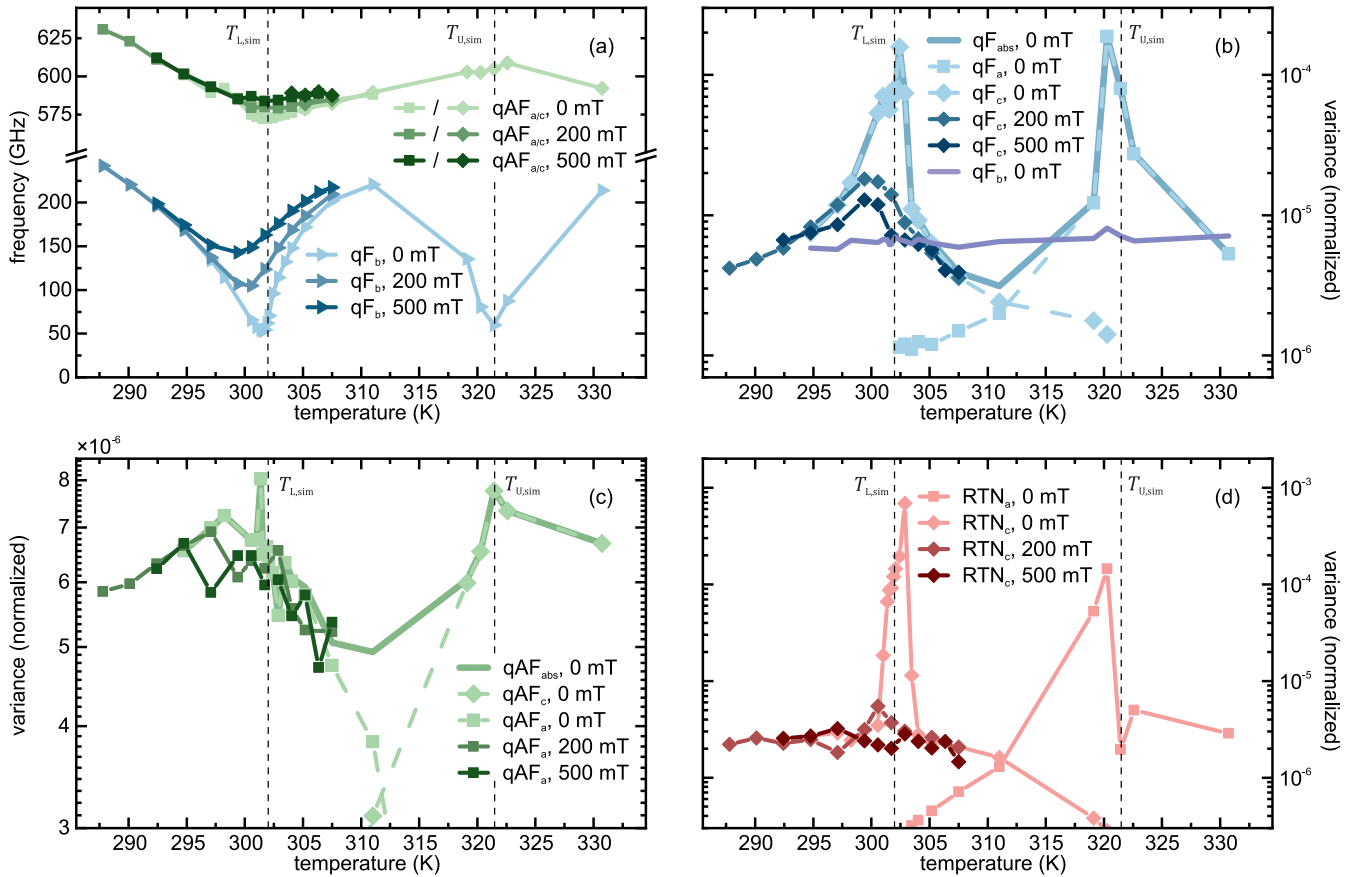


FIG. 10. Frequencies and variances of simulated spin noise in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ along different crystallographic directions. (a) Frequency of the quasiferromagnetic (qF, blue) and quasi-antiferromagnetic (green, qAF) magnon modes along the a axis (squares), b axis (triangles), and c axis (diamonds) as a function of temperature. The dotted vertical lines indicate the lower and upper critical temperatures T_L and T_U of the spin-reorientation transition. (b) qF mode variances as a function of temperature along the a axis (blue squares), b axis (purple line), and c axis (blue diamonds). The blue solid line represents the absolute values (abs) of the a - and c -axis data points. (c) qAF mode variances as a function of temperature along the a axis (green squares) and c axis (green diamonds). (d) Variances of the random telegraph fluctuations along the a axis (red squares) and c axis (red diamonds).

Finally, Fig. 10(d) presents the RTN amplitude as a function of temperature and applied magnetic field. RTN appears along the c axis near $T_{L,\text{sim}}$ and along the a axis near $T_{U,\text{sim}}$, in agreement with the Monte Carlo simulations. The

application of external magnetic fields strongly suppresses RTN, which we attribute to asymmetric shifting of the potential minima and the associated increase in the effective potential barrier.

- [1] F. Bloch, Nuclear induction, *Phys. Rev.* **70**, 460 (1946).
- [2] F. Keffer and C. Kittel, Theory of antiferromagnetic resonance, *Phys. Rev.* **85**, 329 (1952).
- [3] T. Jungwirth, X. Marti, P. Wadley, and J. Wunderlich, Antiferromagnetic spintronics, *Nat. Nanotechnol.* **11**, 231 (2016).
- [4] E. V. Gomonay and V. M. Loktev, Spintronics of antiferromagnetic systems (Review Article), *Low Temp. Phys.* **40**, 17 (2014).
- [5] D. Bossini *et al.*, Laser-driven quantum magnonics and terahertz dynamics of the order parameter in antiferromagnets, *Phys. Rev. B* **100**, 024428 (2019).
- [6] A. V. Kimel, A. Kirilyuk, P. A. Usachev, R. V. Pisarev, A. M. Balbashov, and T. Rasing, Ultrafast nonthermal control of magnetization by instantaneous photomagnetic pulses, *Nature (London)* **435**, 655 (2005).
- [7] A. V. Kimel, A. Kirilyuk, A. Tsvetkov, R. V. Pisarev, and T. Rasing, Laser-induced ultrafast spin reorientation in the antiferromagnet TmFeO_3 , *Nature (London)* **429**, 850 (2004).
- [8] I.-C. Benea-Chelmus, F. F. Settembrini, G. Scalari, and J. Faist, Electric field correlation measurements on the electromagnetic vacuum state, *Nature (London)* **568**, 202 (2019).
- [9] M. A. Weiss *et al.*, Discovery of ultrafast spontaneous spin switching in an antiferromagnet by femtosecond noise correlation spectroscopy, *Nat. Commun.* **14**, 7651 (2023).
- [10] M. A. Weiss, F. S. Herbst, S. Eggert, M. Nakajima, A. Leitenstorfer, S. T. B. Goennenwein, and T. Kurihara, Subharmonic lock-in detection and its optimization for femtosecond noise correlation spectroscopy, *Rev. Sci. Instrum.* **95**, 083005 (2024).

- [11] G. Fitzky, M. Nakajima, Y. Koike, A. Leitenstorfer, and T. Kurihara, Ultrafast control of magnetic anisotropy by resonant excitation of 4f electrons and phonons in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$, *Phys. Rev. Lett.* **127**, 107401 (2021).
- [12] M. A. Weiss, F. S. Herbst, G. Skobjin, S. Eggert, M. Nakajima, D. Reustlen, A. Leitenstorfer, S. T. B. Goennenwein, and T. Kurihara, Quantifying the amplitudes of ultrafast magnetization fluctuations in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ using femtosecond noise-correlation spectroscopy, *Phys. Rev. Appl.* **24**, 044021 (2025).
- [13] T. Kurihara, M. Bamba, H. Watanabe, M. Nakajima, and T. Suemoto, Observation of terahertz-induced dynamical spin canting in orthoferrite magnon by magnetorefractive probing, *Commun. Phys.* **6**, 51 (2023).
- [14] R. J. Fairholme, G. P. Gill, and A. Marsh, Magnetic properties of rare earth orthoferrites grown by a floating zone technique, *Mater. Res. Bull.* **6**, 1131 (1971).
- [15] B. Mali, S. Das, and S. Elizabeth, Magnetic characterization of zone-refined rare-earth orthoferrite crystals grown by the optical floating zone method, *Cryst. Growth Des.* **24**, 1003 (2024).
- [16] T. Moriya, Anisotropic superexchange interaction and weak ferromagnetism, *Phys. Rev.* **120**, 91 (1960).
- [17] I. Dzyaloshinsky, A thermodynamic theory of “weak” ferromagnetism of antiferromagnetics, *J. Phys. Chem. Solids* **4**, 241 (1958).
- [18] G. F. Herrmann, Resonance and high frequency susceptibility in canted antiferromagnetic substances, *J. Phys. Chem. Solids* **24**, 597 (1963).
- [19] G. F. Herrmann, Magnetic resonances and susceptibility in orthoferrites, *Phys. Rev.* **133**, A1334 (1964).
- [20] X. Zhao, K. Zhang, K. Xu, P. Man, T. Xie, A. Wu, G. Ma, S. Cao, and L. Su, Crystal growth and spin reorientation transition in $\text{Sm}_{0.4}\text{Er}_{0.6}\text{FeO}_3$ orthoferrite, *Solid State Commun.* **231–232**, 43 (2016).
- [21] H. Horner and C. M. Varma, Nature of spin-reorientation transitions, *Phys. Rev. Lett.* **20**, 845 (1968).
- [22] S. M. Shapiro, J. D. Axe, and J. P. Remeika, Neutron-scattering studies of spin waves in rare-earth orthoferrites, *Phys. Rev. B* **10**, 2014 (1974).
- [23] L. M. Levinson, M. Luban, and S. Shtrikman, Microscopic model for reorientation of the easy axis of magnetization, *Phys. Rev.* **187**, 715 (1969).
- [24] K. P. Belov, A. K. Zvezdin, A. M. Kadomtseva, and R. Z. Levitin, Spin-reorientation transitions in rare-earth magnets, *Sov. Phys. Uspekhi* **19**, 574 (1976).
- [25] H. Shen, Z. Cheng, F. Hong, J. Xu, S. Yuan, S. Cao, and X. Wang, Magnetic field induced discontinuous spin reorientation in ErFeO_3 single crystal, *Appl. Phys. Lett.* **103**, 192404 (2013).
- [26] K. Yamaguchi, T. Kurihara, Y. Minami, M. Nakajima, and T. Suemoto, Terahertz time-domain observation of spin reorientation in orthoferrite ErFeO_3 through magnetic free induction decay, *Phys. Rev. Lett.* **110**, 137204 (2013).
- [27] J. Guo, L. Cheng, Z. Ren, W. Zhang, X. Lin, Z. Jin, S. Cao, Z. Sheng, and G. Ma, Magnetic field tuning of spin resonance in TmFeO_3 single crystal probed with THz transient, *J. Phys. Condens. Matter* **32**, 185401 (2020).
- [28] T. Suemoto, K. Nakamura, T. Kurihara, and H. Watanabe, Magnetization-free measurements of spin orientations in orthoferrites using terahertz time domain spectroscopy, *Appl. Phys. Lett.* **107**, 042404 (2015).
- [29] C. Riek, D. V. Seletskiy, A. S. Moskalenko, J. F. Schmidt, P. Krauspe, S. Eckart, S. Eggert, G. Burkard, and A. Leitenstorfer, Direct sampling of electric-field vacuum fluctuations, *Science* **350**, 420 (2015).
- [30] C. Riek, P. Sulzer, M. Seeger, A. S. Moskalenko, G. Burkard, D. V. Seletskiy, and A. Leitenstorfer, Subcycle quantum electrodynamics, *Nature (London)* **541**, 376 (2017).
- [31] Y. Ozeki, Y. Kitagawa, K. Sumimura, N. Nishizawa, W. Umemura, S. Kajiyama, K. Fukui, and K. Itoh, Stimulated Raman scattering microscope with shot noise limited sensitivity using subharmonically synchronized laser pulses, *Opt. Express* **18**, 13708 (2010).
- [32] U. Nowak, Classical spin models, in *Handbook of Magnetism and Advanced Magnetic Materials*, edited by H. Kronmüller and S. S. P. Parkin (Wiley, Chichester, England, 2007).
- [33] T. L. Gilbert, Classics in magnetics a phenomenological theory of damping in ferromagnetic materials, *IEEE Trans. Magn.* **40**, 3443 (2004).
- [34] J. Schlegel, M. Evers, and U. Nowak, Spin-noise spectroscopy as a tool for probing magnetic order, [arXiv:2411.18342](https://arxiv.org/abs/2411.18342).
- [35] N. Metropolis, A. W. Rosenbluth, M. N. Rosenbluth, A. H. Teller, and E. Teller, Equation of state calculations by fast computing machines, *J. Chem. Phys.* **21**, 1087 (1953).
- [36] L. T. Tsymbal, Ya. B. Bazaliy, G. N. Kakazei, Yu. I. Nepochatykh, and P. E. Wigen, Natural behavior of the magnetization under spontaneous reorientation: TmFeO_3 , ErFeO_3 , *Low Temp. Phys.* **31**, 277 (2005).
- [37] L. T. Tsymbal, Y. B. Bazaliy, V. N. Derkachenko, V. I. Kamenev, G. N. Kakazei, F. J. Palomares, and P. E. Wigen, Magnetic and structural properties of spin-reorientation transitions in orthoferrites, *J. Appl. Phys.* **101**, 123919 (2007).
- [38] L. T. Tsymbal, V. I. Kamenev, Ya. B. Bazaliy, D. A. Khara, and P. E. Wigen, Structural properties of ErFeO_3 in the spin-reorientation region, *Phys. Rev. B* **72**, 052413 (2005).
- [39] X. X. Zhang *et al.*, Magnetic behavior and complete high-field magnetic phase diagram of the orthoferrite ErFeO_3 , *Phys. Rev. B* **100**, 054418 (2019).
- [40] M. R. Moldover, G. Sjolander, and W. Weyhmann, Second-order nature of the spin-reorientation phase transitions in YbFeO_3 , *Phys. Rev. Lett.* **26**, 1257 (1971).
- [41] V. Balakrishnan, *Mathematical Physics: Applications and Problems* (Springer Nature, New York, 2020).
- [42] S. Machlup, Noise in semiconductors: Spectrum of a two-parameter random signal, *J. Appl. Phys.* **25**, 341 (1954).
- [43] Ya. B. Bazaliy, L. T. Tsymbal, G. N. Kakazei, A. I. Izotov, and P. E. Wigen, Spin-reorientation in ErFeO_3 Zero-field transitions, three-dimensional phase diagram, and anisotropy of erbium magnetism, *Phys. Rev. B* **69**, 104429 (2004).
- [44] P. A. Usachev, R. V. Pisarev, A. M. Balbashov, A. V. Kimel, A. Kirilyuk, and T. Rasing, Optical properties of thulium orthoferrite TmFeO_3 , *Phys. Solid State* **47**, 2292 (2005).