

Tunable enhancement of magnetization dynamics by selection of the crystallographic orientation of the hybrid interface of exchange-coupled α -Fe₂O₃/permalloy heterostructures

Hassan Al-Hamdo^{1,*}, Tobias Wagner^{2,*}, Philipp Schwenke¹, Gutenberg Kendzo¹, Maximilian Dausend¹, Laura Scheuer¹, Misbah Yaqoob¹, Vitaliy I. Vasyuchka¹, Philipp Pirro¹, Olena Gomonyay², and Mathias Weiler¹

¹*Fachbereich Physik and Landesforschungszentrum OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, 67663 Kaiserslautern, Germany*

²*Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany*



(Received 12 February 2025; accepted 10 April 2025; published 1 May 2025)

We investigate spin dynamics in α -Fe₂O₃/Ni₈₀Fe₂₀ (Py) heterostructures, uncovering a robust mechanism for designing the ferromagnetic resonance (FMR) frequency through control of crystal orientation, temperature, and applied magnetic field. Employing cryogenic ferromagnetic resonance spectroscopy, we demonstrate that the relative orientation of the Néel vector of α -Fe₂O₃ and the magnetization of the Py layer is highly tunable across the Morin transition temperature (T_M). Central to our findings is the pivotal role of crystal orientation in governing the spin dynamics, with the reorientation of the Néel vector serving as a complementary mechanism that further modulates the system's behavior. Our experiments and corroborating theoretical model reveal distinct resonance behavior for different crystal orientations, highlighting the pivotal role of the mutual Néel vector and magnetization geometry in dictating FMR frequencies. In this way, we can tune the FMR frequencies up to a tenfold increase by manipulating the mutual Néel vector/magnetization configuration. Our study comprises all common α -Fe₂O₃ crystal orientations and develops a unified theoretical description of the ensuing spin dynamics.

DOI: [10.1103/PhysRevB.111.L180401](https://doi.org/10.1103/PhysRevB.111.L180401)

Magnetic heterostructures that combine antiferromagnetic (AFM) and ferromagnetic (FM) constituents are widely employed in commercial spintronic devices for sensing and data processing. Continuous research efforts focusing on the physical phenomena underlying the properties of these heterostructures have led to significant improvements of these devices as well as emerging application scenarios [1–10].

While the fully compensated magnetic moments of the AFM layer [11,12] result in remarkable properties on their own, such as the absence of stray fields and terahertz (THz) spin dynamics [11–13], the key requirement for the functional properties of AFM/FM heterostructures is the coupling of the AFM and FM magnetic order [10,14–19]. This coupling gives rise to functional magnetic phenomena, including shifts in the hysteresis loop, enhanced coercivity of the FM layer [14,18,19], rotational hysteresis under high magnetic fields [17], and rotatable anisotropy [20,21]. The strength of this coupling can be modulated by adjusting the thickness of the FM or AFM layers [22–29]. In ferromagnetic resonance experiments, this interfacial coupling also produces effects such as unidirectional anisotropy, increased resonance linewidth,

and shifts in the ferromagnetic resonance field and frequency [16,22,29–31].

Here, we experimentally and theoretically demonstrate that the dependence of the effective anisotropy and ferromagnetic resonance frequency on the relative orientation of Néel vector and magnetization can be exploited to enable *in situ* control of spin dynamics in α -Fe₂O₃/permalloy (Py) heterostructures.

α -Fe₂O₃ is an insulating antiferromagnet (AFM) with a corundum crystal structure [32–35], characterized by a Morin transition at approximately $T_M \approx 260$ K [36,37]. Above T_M , α -Fe₂O₃ behaves as a canted antiferromagnet, exhibiting a small magnetic moment due to the Dzyaloshinskii-Moriya interaction [34,38]. Below T_M , the spins of α -Fe₂O₃ reorient along the *c* axis, leading to the formation of a collinear antiferromagnet. The T_M can be controlled by doping [39–41], and T_M above room temperature has been realized [42].

We study heterostructures based on α -Fe₂O₃ single crystals and a 10-nm-thick polycrystalline Py layer prepared by electron beam evaporation (see Supplemental Material [43] for more details). To demonstrate the control of the mutual Néel vector and magnetization geometry, we investigate the ferromagnetic resonance (FMR) behavior of the FM Py layer coupled to both canted and collinear phases of the α -Fe₂O₃ crystals. By varying the AFM crystal orientation and system temperature, we demonstrate that the AFM/FM spin coupling can be exploited to control the FM resonance frequency via reconfiguration of the relative orientation of the Néel vector and FM magnetization. Because the Néel vector of α -Fe₂O₃ can be configured *in situ* by magnetic fields and temperature,

*These authors contributed equally to this work.

†Contact author: h.alhamdo@rptu.de.

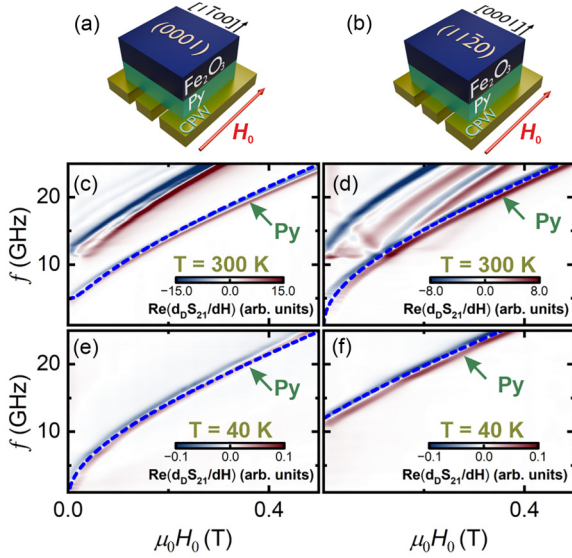


FIG. 1. (a) and (b) Schematic representation of the α -Fe₂O₃/Py heterostructures for the (0001) and (11 $\bar{2}$ 0) samples, respectively. The external magnetic field is applied in plane for both samples. (c), (e) Real part of the background-corrected VNA signal for the (0001) sample at 300 and 40 K, respectively. (d) and (f) display corresponding measurement results for the (11 $\bar{2}$ 0) sample, where H_0 is applied in plane and parallel to the [0001] axis. The dashed blue lines represent the Py resonance frequencies obtained from our model calculations (see text).

our findings present opportunities for tunable FM dynamics in advanced magnetoelectronic devices.

In our experiments, we utilized AFM/FM heterostructures with a range of α -Fe₂O₃ crystal orientations. In the following, we refer to our heterostructures based on their crystal plane orientations: (11 $\bar{2}$ 0), (10 $\bar{1}$ 0), (1 $\bar{1}$ 02), and (0001) (see Supplemental Material [43]).

The spin dynamics of the uniform FM resonance mode in these samples were studied using cryogenic ferromagnetic resonance spectroscopy (cryo-FMR) based on an assembly of a coplanar waveguide connected to a vector network analyzer (VNA) with 43 GHz bandwidth. The investigation was conducted by systematically varying the system temperature from 40 to 400 K.

Figure 1 presents schematics, experimental data, and theoretical modeling for two selected α -Fe₂O₃/Py heterostructures to demonstrate the salient features of Néel vector control of FM spin dynamics.

We first focus on results based on the (0001) heterostructure that is schematically depicted in Fig. 1(a). In Fig. 1(c), we show the FMR spectra and theoretical model obtained at 300 K—well above the Morin transition of α -Fe₂O₃. Specifically, we show the color-coded $\text{Re}(d_0 S_{21}/dH)$ spectra obtained by performing the derivative divide [44] data processing of our raw S_{21} VNA-FMR data. Multiple resonance lines above 10 GHz are observed and attributed to the quasi-FMR response of the cuboid-shaped α -Fe₂O₃ crystal [45]. We observe these modes also in a bare α -Fe₂O₃ crystal without a Py layer (see Supplemental Material [43]). In the following, we focus on the Py resonance because the large volume of

the α -Fe₂O₃ crystal prevents the observation of interfacial effects on its spin dynamics. At lower frequencies, we observe a further single resonance line in Fig. 1(c) that we attribute to the Py FMR response. It is noteworthy that for $H_0 \rightarrow 0$, the FMR frequency is approximately $f = 5$ GHz, while we would expect $f \rightarrow 0$ for an isolated Py film [46,47].

Conversely, Fig. 1(e) presents the FMR spectra recorded at 40 K, where the resonance mode of α -Fe₂O₃ is well outside of the frequency range of our experimental setup due to the transition of α -Fe₂O₃ from canted AFM to collinear AFM. Importantly, we observe that the Py FMR frequency is now approaching $f \rightarrow 0$ for $H_0 \rightarrow 0$. By comparing to Fig. 1(c) we furthermore observe that the Py resonance frequencies at 300 and 40 K are similar at large H_0 .

The right column of Fig. 1 shows the FMR spectra of the (11 $\bar{2}$ 0) heterostructure [see the schematic depiction in Fig. 1(b)]. Again, we recorded the spectra at temperatures above [Fig. 1(d)] and below [Fig. 1(f)] T_M , respectively. At 300 K, in contrast to our corresponding observations from the (0001) sample, we observe no enhancement of the Py resonance frequency for $H_0 \rightarrow 0$. Rather, for this heterostructure we now observe that the FMR spectra exhibit a clearly enhanced Py resonance frequency for $T = 40$ K for all values of H_0 . The corresponding FMR frequency in Fig. 1(f) assumes a value of $f \approx 12$ GHz for $H_0 = 0$, again in contrast to the corresponding observations from the (0001) sample depicted in Fig. 1(e). The linewidth of the Py signal was found to decrease slightly with temperature, with no significant changes observed near or above T_M (see Supplemental Material [43]).

In summary, the experimental data in Fig. 1 strongly indicate that the Py magnetization dynamics reacts to the modification of the relative orientation of the magnetic vectors that can be achieved by varying the temperature across the Morin transition and/or changing the interface orientation of α -Fe₂O₃.

In Fig. 1, the blue dashed lines represent the result of theoretical modeling which is in agreement with the experimental observations. In the following, we will discuss our model to give an intuitive understanding of the underlying phenomena.

We assume a parallel interface coupling between the Néel vector ($\mathbf{n}$) of α -Fe₂O₃ and the Py magnetization vector ($\mathbf{m}_F$) with the corresponding interface energy contribution $w_{\text{int}} = -J_{\text{int}} \xi \mathbf{n} \cdot \mathbf{m}_F$, where $J_{\text{int}} > 0$ is the coupling strength and ξ is the effective thickness of the interface layer. Here, we consider the uniform mode and neglect the inhomogeneous distribution of magnetic order within both Py and α -Fe₂O₃. We also exclude the excitation of the AFM dynamics by focusing on the effective anisotropy of Py induced by the interfacial coupling with α -Fe₂O₃. We also assume that the equilibrium orientation of the Néel vector does not depend on the cut and field value, and is either along the [0001] axis (below T_M), or in the (0001) plane perpendicular to the external magnetic field (above T_M) (see Fig. 1). In contrast, the equilibrium orientation of the Py magnetization depends strongly on the orientation of the crystal cut as the stray fields always keep the Py magnetization in the film plane. It is calculated by minimizing the magnetic energy of the Py layer and the energy of the interfacial exchange coupling with the Néel vector. The full procedure is detailed in the Supplemental Material [43].

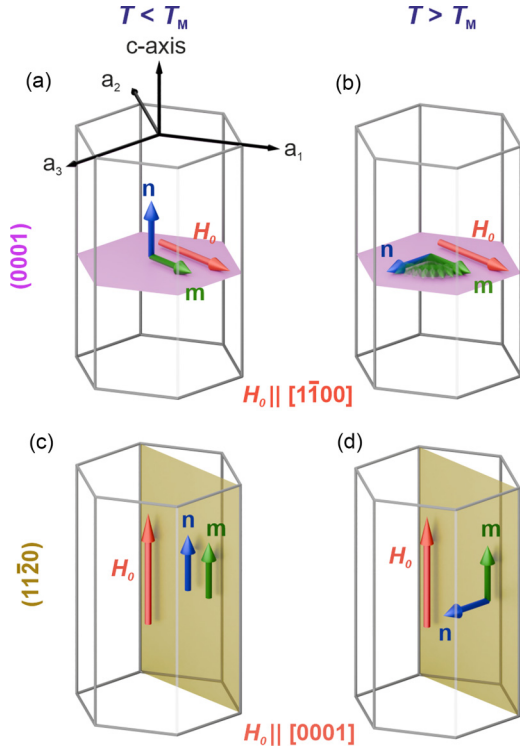


FIG. 2. Schematic depiction of the orientation of the Néel vector of α -Fe₂O₃ ($\mathbf{n}$, blue arrows) and magnetization vector of Py ($\mathbf{m}_F$, green arrows) below [(a) and (c)] and above [(b) and (d)] the Morin transition for different crystal cuts (shaded areas). Red arrows show the orientation of the external magnetic field. The competition of the Zeemann energy and the interfacial coupling with the Néel vector induces a reorientation of the Py magnetization while increasing the magnetic field for $T > T_M$ and (0001) crystal cut as indicated by the transparent green arrows in (b).

Within this model, we find that for the (0001) sample above T_M [Fig. 2(b)], the Py magnetization vector is parallel to the Néel vector in absence of the magnetic field, $\mathbf{n} \parallel \mathbf{m}_F$. The interfacial coupling energy w_{int} in this case reaches the minimum value, thus maximizing the coupling. The external magnetic field $\mathbf{H}_0 \parallel [1\bar{1}00]$ induces a gradual rotation of the Py magnetization away from $\mathbf{n}$, so that the effective coupling is reduced.

Below T_M [Fig. 2(a)], the Néel vector is aligned along the c axis, perpendicular to both the sample plane and the Py magnetization. The application of an in-plane H_0 has no effect on the equilibrium orientation $\mathbf{m}_F$, which always remains orthogonal to $\mathbf{n}$. As a result, in this case $\mathbf{m}_F$ is decoupled from $\mathbf{n}$.

For the (11 $\bar{2}$ 0) sample we find a qualitatively different scenario. In contrast to the (0001) sample, $\mathbf{n}$ and $\mathbf{m}_F$ are completely decoupled above T_M [Fig. 2(d)], where $\mathbf{m}_F \perp \mathbf{n}$, and strongly coupled below T_M , where $\mathbf{m}_F \parallel \mathbf{n}$. We interpret the interface coupling as an effective anisotropy field $H_{\text{int}}(H_0)$ for the Py magnetization, which is reflected in the field dependence of the FMR frequency,

$$f(H_0) = \frac{\mu_0 \gamma}{2\pi} \sqrt{[H_{\text{int}}(H_0) + H_0](M_F + H_0)}, \quad (1)$$

where γ is the gyromagnetic ratio of Py, μ_0 is the vacuum permeability, and M_F is the saturation magnetization of Py. The strength of the anisotropy field $H_{\text{int}}(H_0) = J_{\text{int}} \xi |\mathbf{n}| \cos \varphi_0 (H_0) / d_F$ depends on the interface exchange coupling and thus decays with the thickness d_F of the Py layer. The angle φ_0 between the equilibrium orientation of the Py magnetization and the Néel vector depends on the orientation of the cut and on the value of the magnetic field. For the perpendicular orientation $\mathbf{n} \perp \mathbf{m}_F$, $\mathbf{H}_0$, $\varphi_0 = \pi/2$ [Figs. 2(a) and 2(d)], $H_{\text{int}} = 0$, and the FMR frequency follows the standard Kittel law, resulting in the dashed blue lines in Figs. 1(c) and 1(e). In the case of $\mathbf{n} \parallel \mathbf{m}_F \parallel \mathbf{H}_0$ [Fig. 2(c)], $\varphi_0 = 0$ and $f(H_0)$ dependence shows a gap $\gamma \mu_0 \sqrt{H_{\text{int}} M_F}$, which explains the enhanced Py resonance frequency reaching up to 12 GHz [Fig. 1(f)]. In the intermediate case with $\mathbf{n}$, $\mathbf{m}_F$, and $\mathbf{H}_0$ parallel to the interface [Fig. 2(b)] the angle φ_0 changes from a nonzero equilibrium value at zero field to $\varphi_0 = 0$ at saturation. This results in two distinct regions of $f(H_0)$ [see Fig. 1(b)] below and above the saturation. For more details of the theoretical model we refer the reader to the Supplemental Material [43].

Figure 3(a) shows the effective anisotropy field for vanishing external magnetic field $H_{\text{int}}(H_0 = 0)$ that originates from interfacial coupling only, for both samples, measured across a temperature range from 40 to 400 K. For the (0001) sample, H_{int} remains unchanged at temperatures well below T_M , indicating no modification in the spin configuration of the layers at the interface, in agreement with the schematic of our model shown in Fig. 2(b). At approximately 220 K, an increase in H_{int} is observed, corresponding to the reorientation to parallel alignment of $\mathbf{m}_F$ and $\mathbf{n}$, and the onset of the effective anisotropy induced by interfacial coupling. Above this temperature, H_{int} increases sharply, reaching the saturation value $\mu_0 H_{\text{int}} = 0.03$ T at 270 K.

In contrast, the (11 $\bar{2}$ 0) sample exhibits a maximum $\mu_0 H_{\text{int}} = 0.15$ T at the lowest temperature $T = 40$ K that we set in our experiments [cf. Fig. 2(d)]. When increasing the temperature, near T_M , the value of H_{int} sharply drops and stays $H_{\text{int}} \approx 0$ for $T > T_M$, indicating the decoupling of the Py and α -Fe₂O₃ layers, as shown in Fig. 2(c). In the intermediate-temperature regime below T_M , H_{int} smoothly decreases with increasing temperature. We attribute this to hybridization of the Py and α -Fe₂O₃ modes that is not captured in our didactic macrospin model.

We now discuss the impact of nonzero external magnetic fields $H_0 > 0$ on H_{int} and thus the Py FMR frequency obtained from Eq. (1). To this end, Figs. 3(b) and 3(c) show the relative orientation of the Néel vector and magnetization parametrized by φ_0 as a function of temperature and H_0 as obtained from our model. Figure 3(b) shows the case of the (0001) sample, where the applied magnetic field and the Néel vector are orthogonal [see Figs. 2(a) and 2(b)]. For low temperatures the (0001) sample shows zero H_{int} regardless of the strength of the applied field, as the Néel vector lies perpendicular to the sample plane. Above the Morin transition the Néel vector lies in the sample plane, but perpendicular to the applied field. For low applied fields we observe $\varphi_0 = 0$ and strong interface exchange coupling H_{int} . As the applied magnetic field is increased, the FM magnetization rotates away from

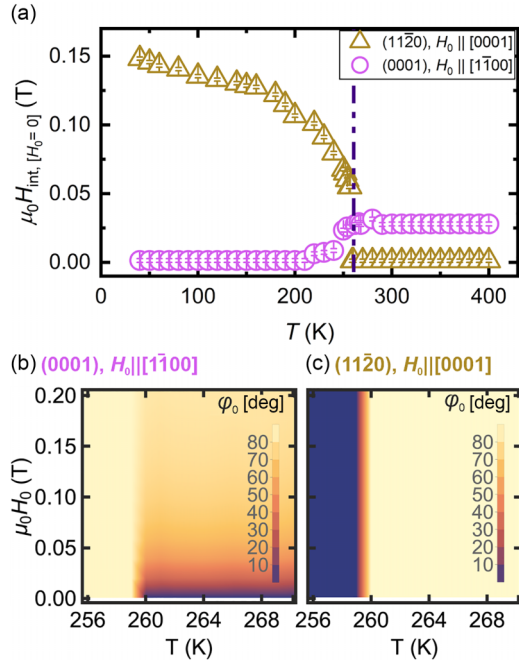


FIG. 3. (a) The effective zero-field interfacial anisotropy, $H_{\text{int}}(0 \text{ T})$, was determined by fitting the FMR spectra (see Fig. 1) with Eq. (1) for the $(11\bar{2}0)$ sample with $H_0 \parallel [0001]$ (gold triangles) and (0001) sample with $H_0 \parallel [1\bar{1}00]$ (magenta circles) over a range of temperatures from 40 to 400 K. (b) and (c) The equilibrium angle ϕ_0 between the AFM Néel vector and the FM magnetization as a function of the applied static magnetic field and temperature for (b) the (0001) -cut sample and (c) the $(11\bar{2}0)$ sample. ϕ_0 in (b) and (c) was calculated by using the experimentally determined interface exchange coupling strength. They show the complementary behavior of the (0001) and the $(11\bar{2}0)$ sample. In each case there are two distinct regions with either low interface exchange coupling (nonzero ϕ_0) or strong interface exchange coupling ($\phi_0 = 0$). (b) additionally showcases the saturation that occurs when the interface exchange coupling competes with the applied magnetic field.

the AFM Néel vector and into alignment with the applied magnetic field, reducing H_{int} .

Figure 3(c) shows the complementary case in the $(11\bar{2}0)$ sample. Here, below the Morin temperature the Néel vector is parallel to the applied field [cf. Fig. 2(d)]. Thus, we observe $\phi_0 = 0$ and strong interface exchange coupling H_{int} with a concomitantly enhanced Py resonance frequency for all applied field strengths in Fig. 1(f). Above the Morin temperature, the Néel vector again points out of the sample plane such that $\phi_0 = \pi/2$. This results in a vanishing H_{int} and an unmodified Py resonance frequency.

To confirm our model, a systematic investigation was carried out using further $\alpha\text{-Fe}_2\text{O}_3/\text{Py}$ systems with various $\alpha\text{-Fe}_2\text{O}_3$ orientations. The external magnetic field was applied in two distinct in-plane directions (see Supplemental Material [43]). The results demonstrate a systematic variation in the Py FMR frequency with changes in temperature, indicating that both the crystal orientation and temperature significantly influence the hybrid spin dynamics of the system.

Figure 4 presents the effective anisotropy, H_{int} , extracted from the fitting of the experimental data for the additional

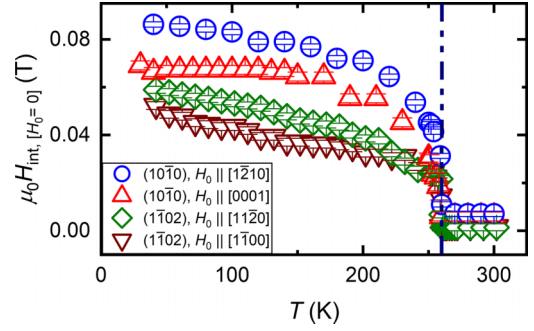


FIG. 4. The effective anisotropy $H_{\text{int}}(0)$ for $(10\bar{1}0)$ with $H_0 \parallel [1\bar{2}10]$ (blue points), $(10\bar{1}0)$ with $H_0 \parallel [0001]$ (red points), $(1\bar{1}02)$ with $H_0 \parallel [1\bar{1}20]$ (green points), and $(1\bar{1}02)$ with H_0 projected along $[1\bar{1}00]$ (brown points). The measurements were conducted over a temperature range of 40–300 K (see Supplemental Material [43]).

samples analyzed in this study. The samples exhibit behavior similar to that of the $(11\bar{2}0)$ orientation with $H \parallel [0001]$ (as shown in Fig. 3): strong coupling below T_M with H_{int} reaching maximum value at 40 K, and zero coupling above T_M . Switching between the coupled and decoupled regime is controlled by the temperature-induced reorientation of the Néel vector. These findings confirm that the strength of H_{int} in $\alpha\text{-Fe}_2\text{O}_3/\text{Py}$ heterostructures is governed by both the crystal structure of $\alpha\text{-Fe}_2\text{O}_3$ and temperature.

In conclusion, our investigation of spin dynamics in $\alpha\text{-Fe}_2\text{O}_3/\text{Py}$ heterostructures reveals the critical role of the relative orientation of Néel vector and magnetization for spin dynamics in AFM/FM heterostructures. By utilizing cryogenic ferromagnetic resonance spectroscopy, we explored the spin dynamics behavior of these heterostructures as a function of crystal orientation of $\alpha\text{-Fe}_2\text{O}_3$ and temperature. Our findings demonstrate that the effective magnetic anisotropy of the ferromagnetic thin film is highly sensitive to both factors, particularly near T_M . Our model highlights the importance of the relative alignment between the Néel vector in $\alpha\text{-Fe}_2\text{O}_3$ and the magnetization vector in Py as key determinants of the spin dynamics. These results provide valuable insights into the manipulation of spin dynamics in AFM/FM heterostructures, offering potential applications in the design of advanced spintronic devices that leverage the geometric control of the mutual Néel vector/magnetization configuration.

We acknowledge financial support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the Transregional Collaborative Research Center TRR 173/3–268565370 “Spin+X” (Projects B15, B13, and B11). O.G. and T.W. also acknowledge support from Deutsche Forschungsgemeinschaft (DFG) SPP 2137, Project No. 403233384. M.W. acknowledges support from the European Research Council (ERC) under the European Union’s Horizon Europe research and innovation program (Grant Agreement No. 101044526).

Data Availability. The data that support the findings of this article are openly available [62], embargo periods may apply.

- [1] K. Li, Y. Wu, Z. Guo, Y. Zheng, G. Han, J. Qiu, P. Luo, L. An, and T. Zhou, Exchange coupling and its applications in magnetic data storage, *J. Nanosci. Nanotechnol.* **7**, 13 (2007).
- [2] C. Chappert, A. Fert, and F. N. Van Dau, The emergence of spin electronics in data storage, *Nat. Mater.* **6**, 813 (2007).
- [3] B. Dieny, V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri, Giant magnetoresistive in soft ferromagnetic multilayers, *Phys. Rev. B* **43**, 1297 (1991).
- [4] J. Nogués and I. K. Schuller, Exchange bias, *J. Magn. Magn. Mater.* **192**, 203 (1999).
- [5] V. Skumryev, S. Stoyanov, Y. Zhang, G. Hadjipanayis, D. Givord, and J. Nogués, Beating the superparamagnetic limit with exchange bias, *Nature (London)* **423**, 850 (2003).
- [6] V. S. Luong, A. T. Nguyen, Q. K. Hoang, T. N. Nguyen, A. T. Nguyen, T. A. Nguyen, and V. C. Giap, Magnetoresistive performances in exchange-biased spin valves and their roles in low-field magnetic sensing applications, *J. Sci.: Adv. Mater. Devices* **3**, 399 (2018).
- [7] Y.-H. Huang, C.-Y. Yang, C.-W. Cheng, A. Lee, C.-H. Tseng, H. Wu, Q. Pan, X. Che, C.-H. Lai, K.-L. Wang *et al.*, A spin-orbit torque ratchet at ferromagnet/antiferromagnet interface via exchange spring, *Adv. Funct. Mater.* **32**, 2111653 (2022).
- [8] Y.-C. Lau, D. Betto, K. Rode, J. Coey, and P. Stamenov, Spin-orbit torque switching without an external field using interlayer exchange coupling, *Nat. Nanotechnol.* **11**, 758 (2016).
- [9] J. Železný, P. Wadley, K. Olejník, A. Hoffmann, and H. Ohno, Spin transport and spin torque in antiferromagnetic devices, *Nat. Phys.* **14**, 220 (2018).
- [10] K. Takano, R. H. Kodama, A. E. Berkowitz, W. Cao, and G. Thomas, Interfacial uncompensated antiferromagnetic spins: Role in unidirectional anisotropy in polycrystalline $\text{Ni}_{81}\text{Fe}_{19}/\text{CoO}$ bilayers, *Phys. Rev. Lett.* **79**, 1130 (1997).
- [11] L. Néel, Propriétés magnétiques de l'état métallique et énergie d'interaction entre atomes magnétiques, *Ann. Phys.* **11**, 232 (1936).
- [12] T. Nagamiya, K. Yosida, and R. Kubo, Antiferromagnetism, *Adv. Phys.* **4**, 1 (1955).
- [13] S. M. Rezende, A. Azevedo, and R. L. Rodríguez-Suárez, Introduction to antiferromagnetic magnons, *J. Appl. Phys.* **126**, 151101 (2019).
- [14] W. H. Meiklejohn and C. P. Bean, New magnetic anisotropy, *Phys. Rev.* **102**, 1413 (1956).
- [15] M. Finazzi, Interface coupling in a ferromagnet/antiferromagnet bilayer, *Phys. Rev. B* **69**, 064405 (2004).
- [16] R. D. McMichael, M. D. Stiles, P. J. Chen, and W. F. Egelhoff, Jr., Ferromagnetic resonance studies of NiO-coupled thin films of $\text{Ni}_{80}\text{Fe}_{20}$, *Phys. Rev. B* **58**, 8605 (1998).
- [17] M. C. Schlenker, Étude des pertes par hystérésis oscillante dans des couches minces multiples avec couplage ferro-antiferromagnétique, *J. Phys. Colloq.* **29**, C2-157 (1968).
- [18] A. D. Lamirand, M. M. Soares, A. Y. Ramos, H. C. N. Tolentino, M. De Santis, J. C. Cezar, A. De Siervo, and M. Jamet, Robust perpendicular exchange coupling in an ultrathin CoO/PtFe double layer: Strain and spin orientation, *Phys. Rev. B* **88**, 140401(R) (2013).
- [19] S. K. Mishra, F. Radu, S. Valencia, D. Schmitz, E. Schierle, H. A. Dürr, and W. Eberhardt, Dual behavior of antiferromagnetic uncompensated spins in NiFe/IrMn exchange biased bilayers, *Phys. Rev. B* **81**, 212404 (2010).
- [20] R. Prosen, J. Holmen, and B. Gran, Rotatable anisotropy in thin permalloy films, *J. Appl. Phys.* **32**, S91 (1961).
- [21] J. Lommel and C. Graham, Jr., Rotatable anisotropy in composite films, *J. Appl. Phys.* **33**, 1160 (1962).
- [22] H. Al-Hamdo, T. Wagner, Y. Lytvynenko, G. Kendzo, S. Reimers, M. Ruhwedel, M. Yaqoob, V. I. Vasyuchka, P. Pirro, J. Sinova *et al.*, Coupling of ferromagnetic and antiferromagnetic spin dynamics in $\text{Mn}_2\text{Au}/\text{NiFe}$ thin film bilayers, *Phys. Rev. Lett.* **131**, 046701 (2023).
- [23] J. Kohlhepp and W. de Jonge, Influence of the FM/AM interface morphology on the exchange coupling in epitaxial Co (001)/fct-Mn (001), *J. Appl. Phys.* **95**, 6840 (2004).
- [24] H. Jung, O. Traistaru, and H. Fujiwara, Effect of the kinds of ferromagnetic layers on exchange coupling strength in IrMn/FM films, *J. Appl. Phys.* **95**, 6849 (2004).
- [25] A. K. Singh and R. Chandra, Thickness dependent interfacial magnetic coupling in $[\text{La}_2\text{NiMnO}_6/\text{LaMnO}_3]$ multilayers, *J. Magn. Magn. Mater.* **448**, 180 (2018).
- [26] A. Beiranvand, M. Liedke, C. Haalisto, V. Lähteenlahti, A. Schulman, S. Granroth, H. Palonen, M. Butterling, A. Wagner, H. Huhtinen *et al.*, Tuned AFM-FM coupling by the formation of vacancy complex in $\text{Gd}_{0.6}\text{Ca}_{0.4}\text{MnO}_3$ thin film lattice, *J. Phys.: Condens. Matter* **33**, 255803 (2021).
- [27] T. Pokhil, D. Song, and E. Linville, Magnetic force microscope study of antiferromagnet-ferromagnet exchange coupled films, *J. Appl. Phys.* **91**, 6887 (2002).
- [28] J. Beik Mohammadi, J. M. Jones, S. Paul, B. Khodadadi, C. K. A. Mewes, T. Mewes, and C. Kaiser, Broadband ferromagnetic resonance characterization of anisotropies and relaxation in exchange-biased IrMn/CoFe bilayers, *Phys. Rev. B* **95**, 064414 (2017).
- [29] W. Stoecklein, S. S. P. Parkin, and J. C. Scott, Ferromagnetic resonance studies of exchange-biased permalloy thin films, *Phys. Rev. B* **38**, 6847 (1988).
- [30] J. Scott, Ferromagnetic resonance studies in the bilayer system $\text{Ni}_{0.80}\text{Fe}_{0.20}/\text{Mn}_{0.50}\text{Fe}_{0.50}$: Exchange anisotropy, *J. Appl. Phys.* **57**, 3681 (1985).
- [31] V. Speriosu, S. Parkin, and C. Wilts, Standing spinwaves in FeMn/NiFe/FeMn exchange-bias structures, *IEEE Trans. Magn.* **23**, 2999 (1987).
- [32] N. Curry, G. Johnston, P. Besser, and A. Morrish, Neutron diffraction measurements on pure and doped synthetic hematite crystals, *Philos. Mag.* **12**, 221 (1965).
- [33] P. Besser, A. Morrish, and C. Searle, Magnetocrystalline anisotropy of pure and doped hematite, *Phys. Rev.* **153**, 632 (1967).
- [34] G. Muench, S. Arajs, and E. Matijević, The morin transition in small $\alpha\text{-Fe}_2\text{O}_3$ particles, *Phys. Status Solidi A* **92**, 187 (1985).
- [35] R. Chevallier, Propriétés magnétiques de l'oxyde ferrique rhomboédrique ($\text{Fe}_2\text{O}_3\alpha$), *J. Phys. Radium* **12**, 172 (1951).
- [36] F. Morin, Magnetic susceptibility of $\alpha\text{-Fe}_2\text{O}_3$ and $\alpha\text{-Fe}_2\text{O}_3$ with added titanium, *Phys. Rev.* **78**, 819 (1950).
- [37] C. Guillaud, Magnetic properties of iron oxide $\alpha\text{-Fe}_2\text{O}_3$, *J. Phys. Radium* **12**, 489 (1951).
- [38] D. Schroeder and R. Nining, Jr., Morin transition in $\alpha\text{-Fe}_2\text{O}_3$ microcrystals, *Phys. Rev. Lett.* **19**, 632 (1967).
- [39] P. Flanders and J. Remeika, Magnetic properties of hematite single crystals, *Philos. Mag.* **11**, 1271 (1965).
- [40] N. Popov, M. Ristić, M. Bošković, M. Perović, S. Musić, D. Stanković, and S. Krehula, Influence of Sn doping on the

- structural, magnetic, optical and photocatalytic properties of hematite (α -Fe₂O₃) nanoparticles, *J. Phys. Chem. Solids* **161**, 110372 (2022).
- [41] S. Krehula, M. Ristić, M. Reissner, S. Kubuki, and S. Musić, Synthesis and properties of indium-doped hematite, *J. Alloys Compd.* **695**, 1900 (2017).
- [42] N. Shimomura, S. P. Pati, Y. Sato, T. Nozaki, T. Shibata, K. Mibu, and M. Sahashi, Morin transition temperature in (0001)-oriented α -Fe₂O₃ thin film and effect of Ir doping, *J. Appl. Phys.* **117**, 17C736 (2015).
- [43] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevB.111.L180401> for detailed information on the properties and characterization of the α -Fe₂O₃ crystals used in this study, including angle-dependent FMR measurements, the fabrication methods and deposition conditions employed for growing Py films on the main crystallographic plane of α -Fe₂O₃, as well as additional experimental data from crystal orientations not presented in the main text. Furthermore, the Supplemental Material provides an in-depth description of the theoretical models utilized to generate the dashed blue lines shown in Fig. 1, accompanied by supplemental data and including Refs. [44,48–61].
- [44] H. Maier-Flaig, S. T. Goennenwein, R. Ohshima, M. Shiraishi, R. Gross, H. Huebl, and M. Weiler, Note: Derivative divide, a method for the analysis of broadband ferromagnetic resonance in the frequency domain, *Rev. Sci. Instrum.* **89**, 076101 (2018).
- [45] R. Damon and J. Eshbach, Magnetostatic modes of a ferromagnetic slab, *J. Appl. Phys.* **31**, S104 (1960).
- [46] Y. Zhao, Q. Song, S.-H. Yang, T. Su, W. Yuan, S. S. Parkin, J. Shi, and W. Han, Experimental investigation of temperature-dependent gilbert damping in permalloy thin films, *Sci. Rep.* **6**, 22890 (2016).
- [47] T. Klemmer, K. Ellis, and B. Van Dover, Ferromagnetic resonance frequency of a thin Mo-permalloy film, *J. Appl. Phys.* **87**, 5846 (2000).
- [48] R. Lebrun, A. Ross, O. Gomonay, V. Baltz, U. Ebels, A.-L. Barra, A. Qaiumzadeh, A. Brataas, J. Sinova, and M. Kläui, Long-distance spin-transport across the Morin phase transition up to room temperature in ultra-low damping single crystals of the antiferromagnet α -Fe₂O₃, *Nat. Commun.* **11**, 6332 (2020).
- [49] S. G. Chou, P. E. Stutzman, S. Wang, E. J. Garboczi, W. F. Egelhoff, and D. F. Plusquellic, High-resolution terahertz optical absorption study of the antiferromagnetic resonance transition in hematite (α -Fe₂O₃), *J. Phys. Chem. C* **116**, 16161 (2012).
- [50] A. H. Morrish, *Canted Antiferromagnetism: Hematite* (World Scientific, Singapore, 1995).
- [51] T. Dannerger, A. Deák, L. Rózsa, E. Galindez-Ruales, S. Das, E. Baek, M. Kläui, L. Szunyogh, and U. Nowak, Magnetic properties of hematite revealed by an *ab initio* parameterized spin model, *Phys. Rev. B* **107**, 184426 (2023).
- [52] A. Rohrbach, J. Hafner, and G. Kresse, *Ab initio* study of the (0001) surfaces of hematite and chromia: Influence of strong electronic correlations, *Phys. Rev. B* **70**, 125426 (2004).
- [53] A. Hill, F. Jiao, P. Bruce, A. Harrison, W. Kockelmann, and C. Ritter, Neutron diffraction study of mesoporous and bulk hematite, α -Fe₂O₃, *Chem. Mater.* **20**, 4891 (2008).
- [54] M. Białek, J. Zhang, H. Yu, and J.-P. Ansermet, Antiferromagnetic resonance in α -Fe₂O₃ up to its Néel temperature, *Appl. Phys. Lett.* **121**, 032401 (2022).
- [55] M. Hamdi, F. Posva, and D. Grundler, Spin wave dispersion of ultra-low damping hematite (α -Fe₂O₃) at GHz frequencies, *Phys. Rev. Mater.* **7**, 054407 (2023).
- [56] H. Wang, R. Yuan, Y. Zhou, Y. Zhang, J. Chen, S. Liu, H. Jia, D. Yu, J.-P. Ansermet, C. Song *et al.*, Long-distance coherent propagation of high-velocity antiferromagnetic spin waves, *Phys. Rev. Lett.* **130**, 096701 (2023).
- [57] R. Lebrun, A. Ross, O. Gomonay, S. A. Bender, L. Baldrati, F. Kronast, A. Qaiumzadeh, J. Sinova, A. Brataas, R. Duine *et al.*, Anisotropies and magnetic phase transitions in insulating antiferromagnets determined by a spin-Hall magnetoresistance probe, *Commun. Phys.* **2**, 50 (2019).
- [58] A. El Kanj, O. Gomonay, I. Bovenster, P. Bortolotti, V. Cros, A. Anane, and R. Lebrun, Antiferromagnetic magnon spintronic based on nonreciprocal and nondegenerated ultra-fast spin-waves in the canted antiferromagnet α -Fe₂O₃, *Sci. Adv.* **9**, eadh1601 (2023).
- [59] G. Nahrwold, J. M. Scholtyssek, S. Motl-Ziegler, O. Albrecht, U. Merkt, and G. Meier, Structural, magnetic, and transport properties of permalloy for spintronic experiments, *J. Appl. Phys.* **108**, 013907 (2010).
- [60] E. Petrovský, E. Herrero-Bervera, T. Harinarayana, and D. Ivers, *The Earth's Magnetic Interior* (Springer, Berlin, 2011), Vol. 1.
- [61] F. Kraushofer, Z. Jakub, M. Bichler, J. Hulva, P. Drmota, M. Weinold, M. Schmid, M. Setvin, U. Diebold, P. Blaha *et al.*, Atomic-scale structure of the hematite α -Fe₂O₃ (1 $\bar{1}$ 02) “R-cut” surface, *J. Phys. Chem. C* **122**, 1657 (2018).
- [62] H. Al-Hamdo, T. Wagner, P. Schwenke, G. Kendzo, M. Dausend, L. Scheuer, M. Yaqoob, V. I. Vasyuchka, P. Pirro, O. Gomonay, and M. Weiler, Zenodo, 2025, <https://doi.org/10.5281/zenodo.14860707>.