

Quantum sensing magnonic number states using a bosonic mode as the probe

Bashab Dey ^{1,*} Sonu Verma ^{1,2} Mathias Weiler ¹ and Akashdeep Kamra ¹

¹*Department of Physics and Research Center OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, 67663 Kaiserslautern, Germany*

²*Institute for High Pressure, Department of Physics, Hanyang University, Seoul 04763, Republic of Korea*



(Received 6 August 2025; revised 10 June 2026; accepted 22 July 2026; published 18 August 2026)

Sensing number states of a magnonic mode has been accomplished using a superconducting qubit by realizing an effective dispersive interaction between the two systems. Here, we theoretically demonstrate that a seemingly classical bosonic mode can be utilized as a probe for resolving the number states of a magnon mode, while outperforming a qubit in various regards as the sensor. Considering another magnon mode in an antiferromagnet as the probe mode, we delineate the required dispersive coupling emerging directly from antiferromagnetic exchange interaction. When a phonon is used as the probe mode, we derive the effective dispersive coupling emerging from the lowest-order nonlinear magnon-phonon interactions. Our two considered examples provide the general design principles for identifying and utilizing a bosonic probe mode for sensing magnonic superpositions in a physical platform of interest.

DOI: [10.1103/PhysRevB.114.084415](https://doi.org/10.1103/PhysRevB.114.084415)

I. INTRODUCTION

Magnons are the low-energy quasiparticle excitations of an ordered magnet. Due to their long lifetime and strong coupling with photons, phonons, and qubits, magnons can offer a promising platform for quantum computation [1–5] and technologies [6]. The experimental observation of superpositions of magnon number states [7,8] and magnon-qubit entanglement [9] has further propelled the research in quantum magnonics [5]. While the classical uniform magnon mode can be detected using techniques such as magnetic resonance spectroscopy [10,11], the time-resolved magneto-optical Kerr effect [12], spin pumping and inverse spin Hall effect [13], resolving the superpositions of its number states has required probing via a qubit [7,8,14–19]. Spectroscopy of the superconducting qubit enables the superposition sensing through magnon number-dependent shifts in the former's frequency endowed by a strong dispersive interaction [7,20]. A similar interaction has also been engineered between a photonic mode and a qubit [21,22], a phononic mode and a qubit [23–28], two photonic modes [29–33], or two phononic modes [34,35] to study their population statistics.

Recent breakthroughs in quantum sensing using superconducting [36–40] or spinful defect qubits [41–50] are enabling unprecedented access to phenomena in solid-state systems. To unleash the full potential of this sensing, two questions take a central stage. First, to what extent is the quantum nature of

the qubit fundamental in the sensing protocols? Second, given that good qubits are harder to realize in broad settings, can we achieve similar sensing using some widely available bosonic modes, such as photons or phonons, suited to the specific platform?

The community continues to face challenges in sensing quantum magnonic states using a superconducting qubit, with only a few groups having achieved that in the past decade [7,8,18]. Furthermore, the employed architecture requires cryogenic temperatures and a cavity mode to accomplish the desired dispersive magnon-qubit coupling. In this paper, we theoretically demonstrate an avenue for employing a wide range of platforms towards investigating quantum nature of magnons. We theoretically demonstrate that a simple harmonic/bosonic mode can be used as a probe to resolve the magnon number states. This is achieved via a dispersive cross-Kerr coupling $\hbar\chi\alpha^\dagger\alpha\beta^\dagger\beta$ between the magnon (annihilation operator α) and probe bosonic (annihilation operator β) modes which makes the spectroscopically measured probe frequency depend on the magnon number state (Fig. 1). Considering an antiferromagnetic magnon mode as the probe, we show that the required dispersive coupling is *direct* and results from the exchange interaction in the antiferromagnet. This is in contrast to the case of a superconducting qubit, where the dispersive coupling was not direct, but achieved as a higher-order perturbation theory effect [7]. However, to address a broader range of platforms such as a photon or a phonon as the probe mode, we also derive an *effective* dispersive coupling from the lowest-order three-particle interactions between the two modes. We further find that the unbounded energy spectrum of the probe bosonic mode enables it to outperform the qubit as superposition sensor under nonideal conditions, such as higher temperatures and stronger coherent drives employed for quasiclassical probe spectroscopy.

*Contact author: bashab.dey@rptu.de

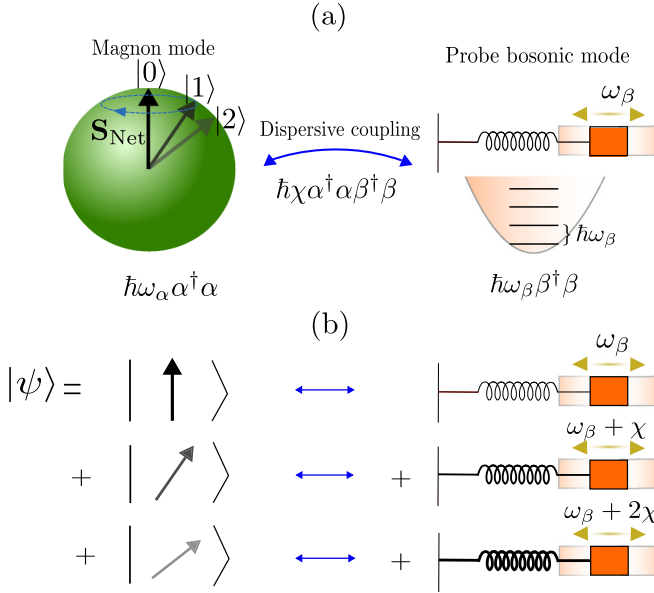


FIG. 1. (a) Schematic depiction of the setup. A uniform magnon mode, with annihilation operator α , is depicted by an arrow representing the total spin $\mathbf{S}_{\text{Net}}$. The tilted arrows represent the excited magnon number states. The probe is a generic harmonic oscillator mode, represented by the annihilation operator β , which interacts with the magnon mode via a dispersive interaction $\hbar\chi\alpha^\dagger\alpha\beta^\dagger\beta$. (b) This dispersive interaction makes the probe mode equivalent spring stiffness and, thus, frequency depend on the magnon number state: $\omega_\beta, \omega_\beta + \chi, \omega_\beta + 2\chi, \dots$, for a superposition of the magnon number states $|0\rangle, |1\rangle, |2\rangle, \dots$.

II. DIRECT DISPERSIVE COUPLING BETWEEN TWO MAGNON MODES

The exchange interaction has recently been shown to cause a direct dispersive coupling between a spin qubit and the magnon mode to be sensed [51,52]. Thus, we may anticipate a similar exchange-induced coupling between the two uniform magnon modes in an antiferromagnet (AFM), with one of them serving as the probe. With this motivation, we first examine an easy-axis anisotropy AFM with $\hat{e}_z$ as the easy axis. In the presence of an external magnetic field $\mathbf{H}_0 = H_0\hat{e}_z$, the Hamiltonian of the AFM is given by $\mathcal{H} = \mathcal{H}_E + \mathcal{H}_A + \mathcal{H}_Z$ with the Heisenberg exchange contribution, $\mathcal{H}_E = \frac{J}{\hbar^2} \sum_i \sum_\delta \mathbf{S}_A(\mathbf{r}_i) \cdot \mathbf{S}_B(\mathbf{r}_i + \delta)$, the easy-axis anisotropy $\mathcal{H}_A = -\frac{K}{\hbar^2} (\sum_i [S_A^z(\mathbf{r}_i)]^2 + \sum_j [S_B^z(\mathbf{r}_j)]^2)$, and the Zeeman term $\mathcal{H}_Z = -\gamma\mu_0 H_0 [\sum_i S_A^z(\mathbf{r}_i) + \sum_j S_B^z(\mathbf{r}_j)]$. Here, $J > 0$ is the strength of the antiferromagnetic exchange interaction, $K > 0$ parametrizes the easy-axis anisotropy, and γ is the gyromagnetic ratio. Indices i and j , representing sites on sublattices A and B, respectively, span the entire set of N unit cells. The summation $\sum_\delta$ in the exchange interaction accounts for all q nearest-neighbor sites. The ground state of this system is an antiferromagnetically ordered state with the Néel vector oriented along the z axis. Employing Holstein-Primakoff transformations [53–55], the Hamiltonian for uniform magnon ($\mathbf{k} = \mathbf{0}$) modes is obtained as

$$\mathcal{H}_0 = \hbar\omega_\alpha\alpha^\dagger\alpha + \hbar\omega_\beta\beta^\dagger\beta + \hbar\chi\alpha^\dagger\alpha\beta^\dagger\beta, \quad (1)$$

where α and β are the annihilation operators of the eigenmodes [see Supplemental material (SM) [56] for details]. The bare magnon frequencies are $\omega_{\alpha(\beta)} = \omega_0 + (-)\mu_0\gamma H_0$, where $\hbar\omega_0 = 2S\sqrt{K(Jq + K)}$, S is the spin length, and $\chi = -Jq/\hbar N$ the dispersive coupling strength. The dispersive coupling is obtained by retaining terms up to the fourth order in the magnon operators and does not require a specific regime of detuning for its validity. Since the dispersive coupling commutes with the uncoupled magnon modes, the energy eigenstates of (1) are $|n_\alpha\rangle|n_\beta\rangle$ with energies

$$E_{n_\alpha, n_\beta} = \hbar\omega_\alpha n_\alpha + \hbar(\omega_\beta + \chi n_\alpha) n_\beta, \quad (2)$$

where n_α and n_β are the magnon numbers of the two modes. Considering β as the probe bosonic mode, the dispersive coupling manifests itself as the multivalued resonant frequency of the probe oscillator, $\omega_{\text{res}}^{n_\alpha} = \omega_\beta + \chi n_\alpha$, when the magnon mode α has a statistical distribution of the magnon number states $|n_\alpha\rangle$ [Fig. 1(b)].

III. RESOLVING MAGNONIC SUPERPOSITIONS

We consider the probe mode to be driven coherently and the probe response is recorded as a function of the drive frequency. When the magnon mode is in a superposition state $|\psi\rangle = \sum_{n_\alpha} c_{n_\alpha} |n_\alpha\rangle$, the response of the probe mode should peak at a drive frequency of $\omega = \omega_{\text{res}}^{n_\alpha}$ with $n_\alpha = 0, 1, 2, \dots$, the peak heights being proportional to the occupation probabilities $P_{n_\alpha} \equiv |c_{n_\alpha}|^2$ of the corresponding magnon number states. This is analogous to qubit spectroscopy used for the sensing of photon-, magnon-, and phonon-number statistics [7,21,23,51].

We demonstrate the sensing protocol by numerically simulating the corresponding spectroscopy [51,52]. The setup consists of the magnon mode dispersively interacting with the probe bosonic mode, which in turn is coupled to a thermal bath at temperature T [Fig. 2(a)]. A coherent drive $\mathcal{V}(t) = d \cos \omega t (\beta + \beta^\dagger)$ of strength d is applied to the probe. The time evolution of the system is studied by numerically solving the Lindblad master equation [57,58]

$$\frac{d\rho}{dt} = -\frac{i}{\hbar} [\mathcal{H}(t), \rho(t)] + \sum_{n=1,2} C_n \rho(t) C_n^\dagger - \frac{1}{2} \{\rho(t), C_n^\dagger C_n\}, \quad (3)$$

where $\rho(t)$ is the density matrix and $\mathcal{H}(t) \equiv \mathcal{H}_0 + \mathcal{V}(t)$ is the Hamiltonian of the magnon-probe system. The collapse operators $C_1 = \sqrt{\kappa(n_{\text{th}}^\beta + 1)}\beta$ and $C_2 = \sqrt{\kappa n_{\text{th}}^\beta}\beta^\dagger$ characterize energy emission to, and absorption from, the bath, respectively. The decay rate of the probe mode is κ , while its equilibrium thermal occupation is $n_{\text{th}}^\beta = [e^{\hbar\omega_\beta/k_B T} - 1]^{-1}$. The decay in the magnon mode α is implicit in our model as it determines the magnonic distribution $\{P_{n_\alpha}\}$ to be sensed, whose information is contained in $\rho(0)$ [21,22,51]. The magnon decay considered here is equivalent to the Gilbert damping used in the Landau-Lifshitz framework [59]. When a steady state is reached upon driving, the probe excitation $\langle \beta^\dagger \beta \rangle \equiv \text{Tr}[\rho \beta^\dagger \beta]$ peaks at the resonant frequencies $\omega = \{\omega_{\text{res}}^{n_\alpha}\}$ [Fig. 2(a)]. The separation between the peaks is $|\chi|$. At $T = 0$, the excitation at $\omega = \omega_{\text{res}}^{n_\alpha}$ can be written as $\langle \beta^\dagger \beta \rangle_{n_\alpha} = k P_{n_\alpha}$, where k is a proportionality constant depending on d and κ .

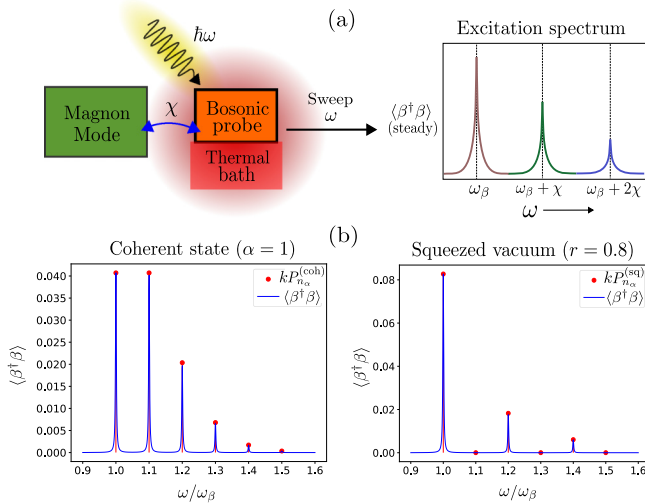


FIG. 2. (a) Schematic depiction of the probe mode spectroscopy. The bosonic probe is coupled to a thermal bath at temperature T and coherently driven. The drive frequency ω is swept and the steady state probe mode excitation $\langle \beta^\dagger \beta \rangle$ is plotted as a function of ω . Peaks appear at multiple frequencies corresponding to unique number states in the magnonic distribution being sensed. (b) Simulation data of the spectroscopy when the magnon mode is in a coherent state (left) with $\alpha = 1$ and squeezed vacuum (right). With α as the coherent state amplitude and r the squeezing factor, the parameters used in the simulation are $\alpha = 1.0$, $r = 0.8$, $\chi/\omega_\beta = 0.1$, $d/\hbar\omega_\beta = 0.001$, $\kappa/\omega_\beta = 0.003$, and $k_B T/\hbar\omega_\beta = 0.01$. The blue curves showing the numerically simulated spectroscopic peaks are in good agreement with the exact probability distributions of the magnon number states shown by the red dots.

As a demonstrative example, we present the simulation data for the magnon mode being in two states, coherent state (classical) and squeezed vacuum (nonclassical), with the bath at zero temperature [Fig. 2(b)]. Here, $\{P_{n_\alpha}^{(\text{coh})}\}$ and $\{P_{n_\alpha}^{(\text{sq})}\}$ are the exact probability distributions of the number states in the coherent state and squeezed vacuum, respectively [60]. Upon extracting the proportionality constant k from the normalization condition (see SM [56]), we find that the simulated peaks

$\langle \beta^\dagger \beta \rangle_{n_\alpha}$ are in good agreement with $kP_{n_\alpha}^{(\text{coh})}$ and $kP_{n_\alpha}^{(\text{sq})}$ shown via red dots in the figure. This validates the anticipated resolution of magnon number state superpositions using a bosonic mode as the probe. The simulations have been performed using the QUTIP package [61,62].

IV. RESOLVABILITY OF THE MAGNON NUMBER STATES AT FINITE TEMPERATURES

In contrast with the two-level qubit, a bosonic mode at finite temperature occupies several number states. Thus, one may expect finite temperature to be more detrimental to the bosonic mode as a sensor. We examine this question now and find instead that the bosonic mode driven with a coherent drive is more robust than the qubit for sensing the desired magnonic superpositions.

In Fig. 3, we show the spectroscopy simulation data at different temperatures for weak and strong driving. Away from resonance, the probe mode has the mean thermal excitation n_{th}^β , which determines the baselines in spectroscopy plots. At a resonance, the drive additionally excites the probe mode creating a Glauber state [63] which represents the classical mode of oscillation. So, the magnitude of this extra excitation should be independent of temperature and proportional to the driving power [64,65]. This is indeed reflected in the spectroscopy as peak heights, measured from the baseline, do not change with temperature [Fig. 3(a)] and still measure the desired magnon number statistics. The consequent net occupation of the probe at a resonance $\langle \beta^\dagger \beta \rangle_{n_\alpha}$ is derived as (see SM [56] for details)

$$\langle \beta^\dagger \beta \rangle_{n_\alpha} = kP_{n_\alpha} + n_{\text{th}}^\beta, \quad (4)$$

where $k = d^2/\hbar^2\kappa^2$ and kP_{n_α} is the peak height from the baseline. At high temperatures and weak driving, the peak heights are much smaller than n_{th}^β which can limit their detectability. This issue is circumvented by driving the probe stronger so that the peaks are high enough [Fig. 3(b)] without compromising their proportionality to the magnon number statistics being sensed.

The resonant peaks and their immunity to temperature can be understood intuitively in terms of the quantum transitions that occur between the energy levels $|n_\alpha\rangle|n_\beta\rangle$ of the system.

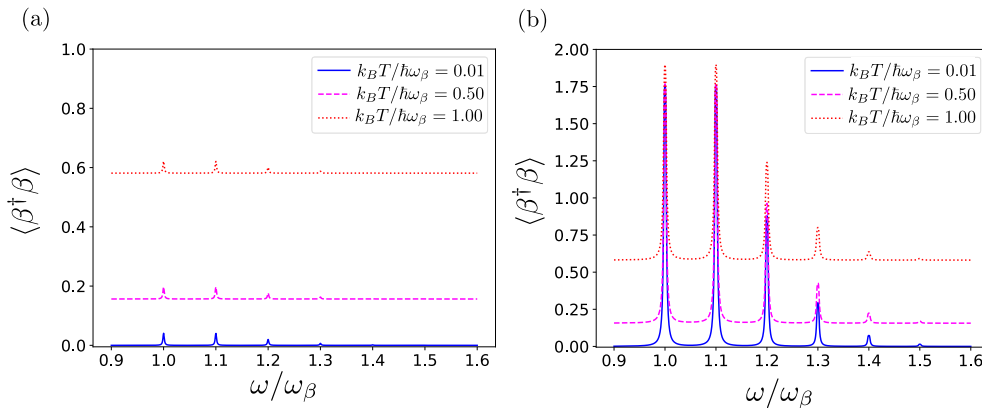


FIG. 3. Simulation results of the probe spectroscopy at different temperatures for a (a) weak drive ($d/\hbar\omega_\beta = 0.001$) and (b) a strong drive ($d/\hbar\omega_\beta = 0.01$). With an increase in temperature, the mean thermal occupation n_{th}^β of the probe mode rises. For weak driving, the spectroscopy peaks are small as compared to n_{th}^β , leading to poor experimental detectability. A stronger drive enhances the peaks making them detectable.

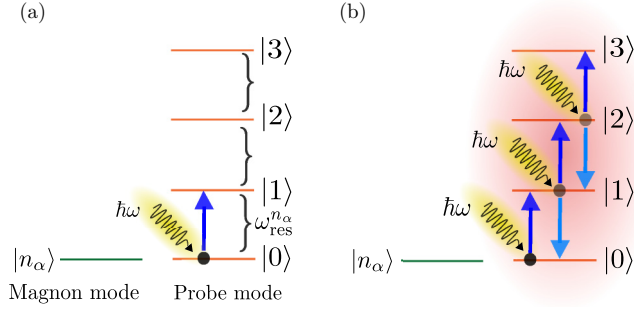


FIG. 4. Schematic depiction of the quantum transitions in the probe mode. (a) At $T = 0$, a photon is resonantly absorbed at $\omega = \omega_{\text{res}}$ causing a transition $|n_\alpha\rangle|0\rangle \rightarrow |n_\alpha\rangle|1\rangle$. (b) At $T \neq 0$, the probe mode has a thermal distribution of the boson number states. Stimulated absorptions (up arrow) and emissions (down arrow) occur between adjacent levels. The probe still remains a simple harmonic oscillator as the energy levels remain equally spaced, i.e., $\Delta = \hbar\omega_{\text{res}}^{n_\alpha}$ despite the superposition of the magnon number states. This makes the bosonic probe a robust sensor of the magnon number statistics even at finite temperatures.

The energy difference between any two levels is

$$E_{n'_\alpha, n'_\beta} - E_{n_\alpha, n_\beta} = \hbar[\omega_\alpha(n'_\alpha - n_\alpha) + \omega_\beta(n'_\beta - n_\beta) + \chi(n'_\alpha n'_\beta - n_\alpha n_\beta)]. \quad (5)$$

The drive $\sim f(\omega t)(\beta + \beta^\dagger)$ only couples levels for which $n'_\alpha = n_\alpha$ and $n'_\beta = n_\beta \pm 1$. The corresponding energy difference is

$$E_{n_\alpha, n_\beta \pm 1} - E_{n_\alpha, n_\beta} = \pm \hbar(\omega_\beta + \chi n_\alpha) = \pm \hbar\omega_{\text{res}}^{n_\alpha}, \quad (6)$$

which is independent of the probe mode occupation n_β . Hence, within linear response, the drive causes resonant transitions $|n_\alpha\rangle|n_\beta\rangle \rightarrow |n_\alpha\rangle|n_\beta \pm 1\rangle$ when $\omega = \omega_{\text{res}}^{n_\alpha}$. A schematic of the quantum transitions at a resonance is shown in Fig. 4 for zero and finite temperatures of the probe. At $T = 0$, the probe mode is in its ground state and a resonant transition $|n_\alpha\rangle|0\rangle \rightarrow |n_\alpha\rangle|1\rangle$ occurs when $\omega = \omega_{\text{res}}^{n_\alpha}$ [Fig. 4(a)]. At $T \neq 0$, the probe levels are thermally populated. So, both stimulated absorptions $|n_\alpha\rangle|n_\beta\rangle \rightarrow |n_\alpha\rangle|n_\beta + 1\rangle$ and emissions $|n_\alpha\rangle|n_\beta\rangle \rightarrow |n_\alpha\rangle|n_\beta - 1\rangle$ occur upon driving at the same frequency $\omega_{\text{res}}^{n_\alpha}$, as shown by up arrows and down arrows, respectively, in Fig. 4(b). Since the resonant frequency is independent of the boson number n_β , it is not modified by the thermal distribution of the probe number states and the spectroscopy protocol for sensing the magnon number statistics in the α mode remains valid.

Due to its two-level nature, a qubit is constrained with respect to its maximum excitation [66]. The latter needs to remain small for the spectroscopy to reveal the desired magnonic statistics [51]. This constraint gets lifted when using a bosonic mode as the probe since it has an infinitely large Hilbert space, thereby enabling effective sensing at higher temperatures. A detailed simulation and comparison presented in the SM [56] corroborates this superiority of the bosonic mode over the qubit as a sensor.

V. EFFECTIVE DISPERSIVE INTERACTION BETWEEN A MAGNON AND PHONON MODE

Unlike the case of an AFM, there may not be a direct dispersive interaction between the magnon mode to be sensed and a generic probe bosonic mode. However, an effective dispersive interaction could be engineered in a wide range of systems that do not host direct dispersive coupling. For example, the linear coherent coupling between a qubit and bosonic mode results in an effective dispersive coupling in the detuned limit [20,67–69].

Magnomechanical interactions in a ferromagnet also result in magnon-phonon couplings [70] that are linear $\sim \alpha^\dagger \beta + \text{H.c.}$ [71] or quadratic $\propto \alpha^{\dagger 2} \beta, \alpha^2 \beta, \alpha^\dagger \alpha \beta + \text{H.c.}$ [72–75] in the magnon operators, where α and β are the annihilation operators of the magnon and phonon modes respectively. Among the quadratic ones, only the parametric coupling $\sim \alpha^\dagger \alpha \beta + \text{H.c.}$ is considered relevant in the far-detuned limit [73,76–80]. In our analysis, we find that the linear $\sim \alpha^\dagger \beta + \text{H.c.}$ and parametric couplings $\sim \alpha^\dagger \alpha \beta + \text{H.c.}$ do not generate any dispersive interaction in the far-detuned limit (see SM [56]) while the parametric conversion $\sim \alpha^{\dagger 2} \beta + \text{H.c.}$ and the counterrotating terms $\sim \alpha^2 \beta + \text{H.c.}$ do. To establish design principles, we consider the most general three-particle interaction,

$$V_{\text{int}} = \hbar\chi_1(\alpha^\dagger \beta^2 + \alpha \beta^{\dagger 2}) + \hbar\chi_2(\alpha \beta^2 + \alpha^\dagger \beta^{\dagger 2}) + \hbar\chi_3(\alpha^2 \beta^\dagger + \alpha^{\dagger 2} \beta) + \hbar\chi_4(\alpha^2 \beta + \alpha^{\dagger 2} \beta^\dagger). \quad (7)$$

In the far-detuned limit, a Schrieffer-Wolff transformation [81,82] on the magnon-phonon Hamiltonian $H_{\text{mp}} = \hbar\omega_\alpha \alpha^\dagger \alpha + \hbar\omega_\beta \beta^\dagger \beta + V_{\text{int}}$ gives an effective Hamiltonian

$$[H_{\text{mp}}]_{\text{eff}} = \hbar\omega_\alpha \alpha^\dagger \alpha + \hbar\omega_\beta \beta^\dagger \beta + \hbar\chi_{\text{eff}} \alpha^\dagger \alpha \beta^\dagger \beta, \quad (8)$$

where

$$\chi_{\text{eff}} = -\frac{4\chi_1^2}{2\omega_\beta - \omega_\alpha} - \frac{4\chi_2^2}{2\omega_\beta + \omega_\alpha} + \frac{4\chi_3^2}{\omega_\beta - 2\omega_\alpha} - \frac{4\chi_4^2}{\omega_\beta + 2\omega_\alpha} \quad (9)$$

is the effective dispersive strength (see SM [56] for details). While we mention a phonon mode as a probe here, our analysis is generic and applies to any bosonic mode that bears the required nonlinear coupling with the magnon mode to be sensed.

VI. PHYSICAL REALIZATION

Considering the AFM with exchange-mediated direct dispersive coupling as the platform, hematite in its easy-plane anisotropy phase hosts a high-frequency magnon mode in the sub-THz regime and a low-frequency one in the few GHz range [83–87]. One may utilize the latter for sensing the magnonic superpositions in the former at moderately high temperatures. Since we show that a finite temperature is not a major problem for the probe mode, the desired sensing of the superpositions is feasible. The design principles for using an AFM magnon or phonon mode as the probe have been detailed in the SM [56]. We deduce that the direct dispersive strength $\chi \propto 1/V$, where V is the volume of the sample. Since the linewidth of the low-frequency resonance in hematite can be several tens of MHz [84], the spectroscopic peaks should

be resolvable for nanometer-sized samples [88–91] where the dispersive shift $\chi/2\pi$ can be in the low or sub-GHz regime. Considering a phonon mode as the probe, we show that the strength of the parametric down-conversion-type coupling χ_3 in Eq. (7) varies as $1/\sqrt{V}$. We estimate that χ_3 can go up to few tens of MHz for thin ferromagnetic films [75,92]. Choosing a moderately large detuning of $\sim 6\chi_3$, the dispersive shift $\chi_{\text{eff}}/2\pi$ can be of the order of MHz. Using a phononic mode as the probe for ferromagnetic magnons offers more control over the effective dispersive coupling as the detuning can be optimally chosen for maximizing χ_{eff} .

Apart from the dispersive term, Kerr-like nonlinearities ($\sim \alpha^{\dagger 2} \alpha^2, \beta^{\dagger 2} \beta^2$), frequency-pulling ($\sim \alpha^{\dagger} \alpha, \beta^{\dagger} \beta$) and mixed terms ($\sim \alpha^{\dagger 2} \beta^{\dagger} \beta$, etc.) also appear in the full Hamiltonians of Eqs. (1) and (8). The Kerr nonlinearity [64,93,94] renders the driven probe nonclassical due to which the resolution of the superpositions is affected at finite temperature, as detailed in the SM [56]. The Kerr nonlinearity arises in the probe mode (β) due to the nonlinear couplings $\propto \chi_1$ and χ_2 in Eq. (7). Choosing the operating point in the frequencies that maximizes the contribution of χ_3 or χ_4 in χ_{eff} [Eq. (9)] automatically suppresses the corresponding contributions from χ_1 or χ_2 (see SM [56]). The frequency-pulling term creates only a global shift in the frequencies of the two modes, which does not affect the simulation results.

To conclude, we have demonstrated how the probability distribution of the number states of a magnon eigenmode can be sensed using a bosonic probe by coupling it to the magnon mode dispersively. The spectroscopy works well even at high temperatures and stronger driving of the probe mode,

which offers a significant advantage over the use of a qubit for this sensing. The dispersive coupling, necessary for the sensing, can be direct or effective. For selected platforms, direct dispersive coupling can be dominant, while for some others, effective dispersive coupling may be more suitable. We discussed two concrete examples of the probe mode, a magnon mode of an AFM and a phonon mode of a ferromagnet, but any bosonic mode can be used. Our analysis lays the groundwork for identifying and utilizing the optimal bosonic probe modes in a given system of interest for quantum manipulation and sensing of superpositions.

Note added. Recently, we became aware of a related work investigating and demonstrating the cross-Kerr interaction with magnons [95].

ACKNOWLEDGMENTS

We thank Takis Kontos for informing us about his related unpublished work and subsequent discussions. We thank the German Research Foundation (DFG) for funding via Spin + X TRR 173-268565370, projects A13 and B13. S.V. acknowledges support from the Brain Pool Program funded by the Ministry of Science and ICT through the National Research Foundation of Korea (RS-2025-25446099).

DATA AVAILABILITY

The data that support the findings of this article are openly available [98].

- [1] S. N. Andrianov and S. A. Moiseev, Magnon qubit and quantum computing on magnon Bose-Einstein condensates, *Phys. Rev. A* **90**, 042303 (2014).
- [2] B. Hetényi, A. Mook, J. Klinovaja, and D. Loss, Long-distance coupling of spin qubits via topological magnons, *Phys. Rev. B* **106**, 235409 (2022).
- [3] B. M. Terhal, J. Conrad, and C. Vuillot, Towards scalable bosonic quantum error correction, *Quantum Sci. Technol.* **5**, 043001 (2020).
- [4] M. Bejarano, F. J. T. Goncalves, T. Hache, M. Hollenbach, C. Heins, T. Hula, L. Körber, J. Heinze, Y. Berencén, M. Helm, J. Fassbender, G. V. Astakhov, and H. Schultheiss, Parametric magnon transduction to spin qubits, *Sci. Adv.* **10**, eadi2042 (2024).
- [5] H. Yuan, Y. Cao, A. Kamra, R. A. Duine, and P. Yan, Quantum magnonics: When magnon spintronics meets quantum information science, *Phys. Rep.* **965**, 1 (2022).
- [6] A. Laucht, F. Hohls, N. Ubbelohde, M. Fernando Gonzalez-Zalba, D. J. Reilly, S. Stobbe, T. Schröder, P. Scarlino, J. V. Koski, A. Dzurak, C.-H. Yang, J. Yoneda, F. Kuemmeth, H. Bluhm, J. Pla, C. Hill, J. Salfi, A. Oiwa, J. T. Muhonen, E. Verhagen, *et al.*, Roadmap on quantum nanotechnologies, *Nanotechnology* **32**, 162003 (2021).
- [7] D. Lachance-Quirion, Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki, and Y. Nakamura, Resolving quanta of collective spin excitations in a millimeter-sized ferromagnet, *Sci. Adv.* **3**, e1603150 (2017).
- [8] D. Xu, X.-K. Gu, H.-K. Li, Y.-C. Weng, Y.-P. Wang, J. Li, H. Wang, S.-Y. Zhu, and J. Q. You, Quantum control of a single magnon in a macroscopic spin system, *Phys. Rev. Lett.* **130**, 193603 (2023).
- [9] D. Xu, X.-K. Gu, Y.-C. Weng, H.-K. Li, Y.-P. Wang, S.-Y. Zhu, and J. Q. You, Macroscopic Bell state between a millimeter-sized spin system and a superconducting qubit, *Quantum Sci. Technol.* **9**, 035002 (2024).
- [10] W. A. Yager and R. M. Bozorth, Ferromagnetic resonance at microwave frequencies, *Phys. Rev.* **72**, 80 (1947).
- [11] F. M. Johnson and A. H. Nethercot, Antiferromagnetic resonance in MnF_2 , *Phys. Rev.* **114**, 705 (1959).
- [12] E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, Ultrafast spin dynamics in ferromagnetic nickel, *Phys. Rev. Lett.* **76**, 4250 (1996).
- [13] Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, Enhanced Gilbert damping in thin ferromagnetic films, *Phys. Rev. Lett.* **88**, 117601 (2002).
- [14] Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki, K. Usami, and Y. Nakamura, Coherent coupling between a ferromagnetic magnon and a superconducting qubit, *Science* **349**, 405 (2015).
- [15] D. Lachance-Quirion, Y. Tabuchi, A. Gloppe, K. Usami, and Y. Nakamura, Hybrid quantum systems based on magnonics, *Appl. Phys. Express* **12**, 070101 (2019).
- [16] D. Lachance-Quirion, S. P. Wolski, Y. Tabuchi, S. Kono, K. Usami, and Y. Nakamura, Entanglement-based single-shot

- detection of a single magnon with a superconducting qubit, *Science* **367**, 425 (2020).
- [17] S. P. Wolski, D. Lachance-Quirion, Y. Tabuchi, S. Kono, A. Noguchi, K. Usami, and Y. Nakamura, Dissipation-based quantum sensing of magnons with a superconducting qubit, *Phys. Rev. Lett.* **125**, 117701 (2020).
 - [18] S. Rani, X. Cao, A. E. Baptista, A. Hoffmann, and W. Pfaff, High-dynamic-range quantum sensing of magnons and their dynamics using a superconducting qubit, *Phys. Rev. Appl.* **23**, 064032 (2025).
 - [19] M. Dols, S. Sharma, L. Bechara, Y. M. Blanter, M. Kounalakis, and S. Viola Kusminskiy, Magnon-mediated quantum gates for superconducting qubits, *Phys. Rev. B* **110**, 104416 (2024).
 - [20] J. G. Peixoto de Faria and M. C. Nemes, Dissipative dynamics of the Jaynes-Cummings model in the dispersive approximation: Analytical results, *Phys. Rev. A* **59**, 3918 (1999).
 - [21] D. I. Schuster, A. A. Houck, J. A. Schreier, A. Wallraff, J. M. Gambetta, A. Blais, L. Frunzio, J. Majer, B. Johnson, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Resolving photon number states in a superconducting circuit, *Nature (London)* **445**, 515 (2007).
 - [22] J. Gambetta, A. Blais, D. I. Schuster, A. Wallraff, L. Frunzio, J. Majer, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Qubit-photon interactions in a cavity: Measurement-induced dephasing and number splitting, *Phys. Rev. A* **74**, 042318 (2006).
 - [23] P. Arrangoiz-Arriola, E. A. Wollack, Z. Wang, M. Pechal, W. Jiang, T. P. McKenna, J. D. Witmer, R. Van Laer, and A. H. Safavi-Naeini, Resolving the energy levels of a nanomechanical oscillator, *Nature (London)* **571**, 537 (2019).
 - [24] L. R. Sletten, B. A. Moores, J. J. Viennot, and K. W. Lehnert, Resolving phonon Fock states in a multimode cavity with a double-slit qubit, *Phys. Rev. X* **9**, 021056 (2019).
 - [25] E. A. Wollack, A. Y. Cleland, R. G. Gruenke, Z. Wang, P. Arrangoiz-Arriola, and A. H. Safavi-Naeini, Quantum state preparation and tomography of entangled mechanical resonators, *Nature (London)* **604**, 463 (2022).
 - [26] U. von Lüpke, Y. Yang, M. Bild, L. Michaud, M. Fadel, and Y. Chu, Parity measurement in the strong dispersive regime of circuit quantum acoustodynamics, *Nat. Phys.* **18**, 794 (2022).
 - [27] N. R. A. Lee, Y. Guo, A. Y. Cleland, E. A. Wollack, R. G. Gruenke, T. Makihara, Z. Wang, T. Rajabzadeh, W. Jiang, F. M. Mayor, P. Arrangoiz-Arriola, C. J. Sarabalis, and A. H. Safavi-Naeini, Strong dispersive coupling between a mechanical resonator and a fluxonium superconducting qubit, *PRX Quantum* **4**, 040342 (2023).
 - [28] A. Y. Cleland, E. A. Wollack, and A. H. Safavi-Naeini, Studying phonon coherence with a quantum sensor, *Nat. Commun.* **15**, 4979 (2024).
 - [29] G. J. Milburn and D. F. Walls, Quantum nondemolition measurements via quadrature coupling, *Phys. Rev. A* **28**, 2065 (1983).
 - [30] N. Imoto, H. A. Haus, and Y. Yamamoto, Quantum nondemolition measurement of the photon number via the optical Kerr effect, *Phys. Rev. A* **32**, 2287 (1985).
 - [31] W. J. Munro, K. Nemoto, R. G. Beausoleil, and T. P. Spiller, High-efficiency quantum-nondemolition single-photon-number-resolving detector, *Phys. Rev. A* **71**, 033819 (2005).
 - [32] F. Helmer, M. Mariani, E. Solano, and F. Marquardt, Quantum nondemolition photon detection in circuit QED and the quantum Zeno effect, *Phys. Rev. A* **79**, 052115 (2009).
 - [33] E. T. Holland, B. Vlastakis, R. W. Heeres, M. J. Reagor, U. Vool, Z. Leghtas, L. Frunzio, G. Kirchmair, M. H. Devoret, M. Mirrahimi, and R. J. Schoelkopf, Single-photon-resolved cross-Kerr interaction for autonomous stabilization of photon-number states, *Phys. Rev. Lett.* **115**, 180501 (2015).
 - [34] C. F. Roos, T. Monz, K. Kim, M. Riebe, H. Häffner, D. F. V. James, and R. Blatt, Nonlinear coupling of continuous variables at the single quantum level, *Phys. Rev. A* **77**, 040302(R) (2008).
 - [35] S. Ding, G. Maslennikov, R. Häblützel, and D. Matsukevich, Cross-Kerr nonlinearity for phonon counting, *Phys. Rev. Lett.* **119**, 193602 (2017).
 - [36] C. L. Degen, F. Reinhard, and P. Cappellaro, Quantum sensing, *Rev. Mod. Phys.* **89**, 035002 (2017).
 - [37] P. S. Patel and D. B. Desai, Review of qubit-based quantum sensing, *Quantum Inf. Process.* **24**, 83 (2025).
 - [38] C. W. Fink, C. P. Salemi, B. A. Young, D. I. Schuster, and N. A. Kurinsky, Superconducting quasiparticle-amplifying transmon: A qubit-based sensor for MeV-scale phonons and single terahertz photons, *Phys. Rev. Appl.* **22**, 054009 (2024).
 - [39] K. Kakuyanagi, H. Toida, L. V. Abdurakhimov, and S. Saito, Submicrometer-scale temperature sensing using quantum coherence of a superconducting qubit, *New J. Phys.* **25**, 013036 (2023).
 - [40] S. Danilin, N. Nugent, and M. Weides, Quantum sensing with tunable superconducting qubits: optimization and speed-up, *New J. Phys.* **26**, 103029 (2024).
 - [41] F. Casola, T. van der Sar, and A. Yacoby, Probing condensed matter physics with magnetometry based on nitrogen-vacancy centres in diamond, *Nat. Rev. Mater.* **3**, 17088 (2018).
 - [42] Y. Xu, W. Zhang, and C. Tian, Recent advances on applications of NV centers; magnetometry in condensed matter physics, *Photonics Res.* **11**, 393 (2023).
 - [43] B. G. Simon, S. Kurdi, J. J. Carmiggelt, M. Borst, A. J. Katan, and T. van der Sar, Filtering and imaging of frequency-degenerate spin waves using nanopositioning of a single-spin sensor, *Nano Lett.* **22**, 9198 (2022).
 - [44] T. van der Sar, F. Casola, R. Walsworth, and A. Yacoby, Nanometre-scale probing of spin waves using single electron spins, *Nat. Commun.* **6**, 7886 (2015).
 - [45] M. R. Page, B. A. McCullian, C. M. Purser, J. G. Schulze, T. M. Nakatani, C. S. Wolfe, J. R. Childress, M. E. McConney, B. M. Howe, P. C. Hammel, and V. P. Bhallamudi, Optically detected ferromagnetic resonance in diverse ferromagnets via nitrogen vacancy centers in diamond, *J. Appl. Phys.* **126**, 124902 (2019).
 - [46] P. E. Dolgirev, S. Chatterjee, I. Esterlis, A. A. Zibrov, M. D. Lukin, N. Y. Yao, and E. Demler, Characterizing two-dimensional superconductivity via nanoscale noise magnetometry with single-spin qubits, *Phys. Rev. B* **105**, 024507 (2022).
 - [47] S. Chatterjee, P. E. Dolgirev, I. Esterlis, A. A. Zibrov, M. D. Lukin, N. Y. Yao, and E. Demler, Single-spin qubit magnetic spectroscopy of two-dimensional superconductivity, *Phys. Rev. Res.* **4**, L012001 (2022).
 - [48] P. Bhattacharyya, W. Chen, X. Huang, S. Chatterjee, B. Huang, B. Kobrin, Y. Lyu, T. J. Smart, M. Block, E. Wang, Z. Wang,

- W. Wu, S. Hsieh, H. Ma, S. Mandyam, B. Chen, E. Davis, Z. M. Geballe, C. Zu, V. Struzhkin, *et al.*, Imaging the Meissner effect in hydride superconductors using quantum sensors, *Nature (London)* **627**, 73 (2024).
- [49] A. L. Melendez, S. Das, F. A. Rodriguez, I.-H. Kao, W. Liu, A. J. Williams, B. Lv, J. Goldberger, S. Chatterjee, S. Singh, and P. C. Hammel, Quantum sensing of broadband spin dynamics and magnon transport in antiferromagnets, *Sci. Adv.* **11**, eadu9381 (2025).
- [50] F. Machado, E. A. Demler, N. Y. Yao, and S. Chatterjee, Quantum noise spectroscopy of dynamical critical phenomena, *Phys. Rev. Lett.* **131**, 070801 (2023).
- [51] A.-L. E. Römling, A. Vivas-Viaña, C. S. Muñoz, and A. Kamra, Resolving nonclassical magnon composition of a magnetic ground state via a qubit, *Phys. Rev. Lett.* **131**, 143602 (2023).
- [52] A.-L. E. Römling and A. Kamra, Quantum sensing of antiferromagnetic magnon two-mode squeezed vacuum, *Phys. Rev. B* **109**, 174410 (2024).
- [53] T. Holstein and H. Primakoff, Field dependence of the intrinsic domain magnetization of a ferromagnet, *Phys. Rev.* **58**, 1098 (1940).
- [54] C. J. Hamer, Zheng Weihong, and P. Arndt, Third-order spin-wave theory for the Heisenberg antiferromagnet, *Phys. Rev. B* **46**, 6276 (1992).
- [55] A. Kamra, E. Thingstad, G. Rastelli, R. A. Duine, A. Brataas, W. Belzig, and A. Sudbø, Antiferromagnetic magnons as highly squeezed Fock states underlying quantum correlations, *Phys. Rev. B* **100**, 174407 (2019).
- [56] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/f8jq-1cxb> for (I) a detailed derivation of the direct dispersive interaction between the two magnon eigenmodes of an antiferromagnet; (II) a description of the spectroscopic setup, numerical simulations, and the procedure for resolving magnonic superpositions; (III) simulation data comparing the performance of a qubit and a bosonic mode as sensors of quantum superpositions; (IV) a derivation of an effective dispersive interaction between a magnon and a phonon mode in the far-detuned limit, with a generalization to other bosonic modes; (V) simulation results demonstrating the influence of Kerr nonlinearity in the probe bosonic mode on sensing at finite temperatures and under strong driving; (VI) Derivations using (A) time-dependent perturbation theory and (B) Lindblad master equation to show the proportionality of spectroscopic peak heights to magnon number statistics; and (VII) Design principles to use (A) an antiferromagnetic magnon or (B) a phonon mode as the probe, which also contains Refs. [96,97].
- [57] H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems* (Oxford University Press, Oxford, UK, 2002).
- [58] G. Lindblad, On the generators of quantum dynamical semigroups, *Commun. Math. Phys.* **48**, 119 (1976).
- [59] H. Y. Yuan, W. P. Sterk, A. Kamra, and R. A. Duine, Master equation approach to magnon relaxation and dephasing, *Phys. Rev. B* **106**, 224422 (2022).
- [60] C. C. Gerry and P. L. Knight, *Introductory Quantum Optics* (Cambridge University Press, Cambridge, UK, 2005).
- [61] J. Johansson, P. Nation, and F. Nori, QuTip: An open-source Python framework for the dynamics of open quantum systems, *Comput. Phys. Commun.* **183**, 1760 (2012).
- [62] J. Johansson, P. Nation, and F. Nori, QuTip 2: A Python framework for the dynamics of open quantum systems, *Comput. Phys. Commun.* **184**, 1234 (2013).
- [63] R. J. Glauber, Coherent and incoherent states of the radiation field, *Phys. Rev.* **131**, 2766 (1963).
- [64] P. D. Drummond and D. F. Walls, Quantum theory of optical bistability. I. Nonlinear polarisability model, *J. Phys. A: Math. Gen.* **13**, 725 (1980).
- [65] C. W. Gardiner and P. Zoller, *Quantum Noise*, 3rd ed. (Springer, Berlin, 2004).
- [66] H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems* (Oxford Academic, Oxford, UK, 2010).
- [67] C. M. Savage, S. L. Braunstein, and D. F. Walls, Macroscopic quantum superpositions by means of single-atom dispersion, *Opt. Lett.* **15**, 628 (1990).
- [68] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation, *Phys. Rev. A* **69**, 062320 (2004).
- [69] D. Zueco, G. M. Reuther, S. Kohler, and P. Hänggi, Qubit-oscillator dynamics in the dispersive regime: Analytical theory beyond the rotating-wave approximation, *Phys. Rev. A* **80**, 033846 (2009).
- [70] E. Abrahams and C. Kittel, Spin-lattice relaxation in ferromagnets, *Phys. Rev.* **88**, 1200 (1952).
- [71] C. A. Potts, E. Varga, V. A. S. V. Bittencourt, S. V. Kusminskiy, and J. P. Davis, Dynamical backaction magnomechanics, *Phys. Rev. X* **11**, 031053 (2021).
- [72] A. Rückriegel, P. Kopietz, D. A. Bozhko, A. A. Serga, and B. Hillebrands, Magnetoelastic modes and lifetime of magnons in thin yttrium iron garnet films, *Phys. Rev. B* **89**, 184413 (2014).
- [73] C. Gonzalez-Ballester, D. Hümmer, J. Gieseler, and O. Romero-Isart, Theory of quantum acoustomagnonics and acoustomechanics with a micromagnet, *Phys. Rev. B* **101**, 125404 (2020).
- [74] V. A. S. V. Bittencourt, C. A. Potts, Y. Huang, J. P. Davis, and S. Viola Kusminskiy, Magnomechanical backaction corrections due to coupling to higher-order Walker modes and Kerr nonlinearities, *Phys. Rev. B* **107**, 144411 (2023).
- [75] K. Küntzle, Y. Kunz, T. Moussa, K. Lasinger, K. Yamamoto, P. Pirro, J. F. Gregg, A. Kamra, and M. Weiler, Magnon-polaron control in a surface magnetoacoustic wave resonator, *Nat. Commun.* **16**, 10116 (2025).
- [76] X. Zhang, C.-L. Zou, L. Jiang, and H. X. Tang, Cavity magnomechanics, *Sci. Adv.* **2**, e1501286 (2016).
- [77] J. Li, S.-Y. Zhu, and G. S. Agarwal, Magnon-photon-phonon entanglement in cavity magnomechanics, *Phys. Rev. Lett.* **121**, 203601 (2018).
- [78] J. Li, S.-Y. Zhu, and G. S. Agarwal, Squeezed states of magnons and phonons in cavity magnomechanics, *Phys. Rev. A* **99**, 021801(R) (2019).
- [79] C. Gonzalez-Ballester, J. Gieseler, and O. Romero-Isart, Quantum acoustomechanics with a micromagnet, *Phys. Rev. Lett.* **124**, 093602 (2020).
- [80] M. Brühlmann, Y. Hwang, J. Puebla, and C. Gonzalez-Ballester, Classical and quantum theory of magnonic and magnetoelastic nonlinear dynamics in continuum geometries, *Phys. Rev. B* **113**, 014430 (2026).

- [81] J. R. Schrieffer and P. A. Wolff, Relation between the Anderson and Kondo Hamiltonians, *Phys. Rev.* **149**, 491 (1966).
- [82] G. T. Landi, Eigenoperator approach to Schrieffer–Wolff perturbation theory and dispersive interactions, *arXiv:2409.10656*.
- [83] A. H. Morrish, *Canted Antiferromagnetism: Hematite* (World Scientific, Singapore, 1995), p. 208.
- [84] I. Boverter, H. T. Simensen, A. Anane, M. Kläui, A. Brataas, and R. Lebrun, Room-temperature antiferromagnetic resonance and inverse spin-Hall voltage in canted antiferromagnets, *Phys. Rev. Lett.* **126**, 187201 (2021).
- [85] H. Wang, Y. Xiao, M. Guo, E. Lee-Wong, G. Q. Yan, R. Cheng, and C. R. Du, Spin pumping of an easy-plane antiferromagnet enhanced by Dzyaloshinskii–Moriya interaction, *Phys. Rev. Lett.* **127**, 117202 (2021).
- [86] J. Chen, Z. Jin, R. Yuan, H. Wang, H. Jia, W. Wei, L. Sheng, J. Wang, Y. Zhang, S. Liu, D. Yu, J.-P. Ansermet, P. Yan, and H. Yu, Observation of coherent gapless magnons in an antiferromagnet, *Phys. Rev. Lett.* **134**, 056701 (2025).
- [87] 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, Tunable enhancement of magnetization dynamics by selection of the crystallographic orientation of the hybrid interface of exchange-coupled α -Fe₂O₃/permalloy heterostructures, *Phys. Rev. B* **111**, L180401 (2025).
- [88] R. D. Zysler, D. Fiorani, A. M. Testa, M. Godinho, E. Agostinelli, and L. Suber, Size effects in the spin-flop transition of hematite nanoparticles, *J. Magn. Magn. Mater.* **272-276**, 1575 (2004).
- [89] K. Vamvakidis, D. Sakellari, M. Angelakeris, and C. Dendrinos-Samara, Size and compositionally controlled manganese ferrite nanoparticles with enhanced magnetization, *J. Nanopart. Res.* **15**, 1743 (2013).
- [90] Z. Yang, Q. Li, Y. Liu, X. Jin, and X. Xing, Unexpected surface superparamagnetism in antiferromagnetic Cr₂O₃ nanoparticles, *RSC Adv.* **5**, 46705 (2015).
- [91] S. Foner, High-field antiferromagnetic resonance in MnF₂, *Phys. Rev.* **130**, 183 (1963).
- [92] Y. Hwang, J. Puebla, K. Kondou, C. Gonzalez-Ballester, H. Isshiki, C. S. Muñoz, L. Liao, F. Chen, W. Luo, S. Maekawa, and Y. Otani, Strongly coupled spin waves and surface acoustic waves at room temperature, *Phys. Rev. Lett.* **132**, 056704 (2024).
- [93] A. Candeloro, S. Razavian, M. Piccolini, B. Teklu, S. Olivares, and M. G. A. Paris, Quantum probes for the characterization of nonlinear media, *Entropy* **23**, 1353 (2021).
- [94] M. Asjad, B. Teklu, and M. G. A. Paris, Joint quantum estimation of loss and nonlinearity in driven-dissipative Kerr resonators, *Phys. Rev. Res.* **5**, 013185 (2023).
- [95] C. Fruy, A. Théry, B. Hue, W. Legrand, L. Jarjat, J. Bally, J. Craquelin, M. R. Delbecq, A. Cottet, and T. Kontos, Observation of strong tripartite coupling in a cavity-quantum circuit-antiferromagnet platform, *Nat. Mater.* (2026).
- [96] I. C. Skogvoll, J. Lidal, J. Danon, and A. Kamra, Tunable anisotropic quantum Rabi model via a magnon–spin-qubit ensemble, *Phys. Rev. Appl.* **16**, 064008 (2021).
- [97] P. Pincus, Theory of magnetic resonance in α -Fe₂O₃, *Phys. Rev. Lett.* **5**, 13 (1960).
- [98] B. Dey, S. Verma, M. Weiler, and A. Kamra, Sensing magnonic quantum superpositions using a bosonic mode as the probe [Dataset], Zenodo, 2025, <https://doi.org/10.5281/zenodo.16752740>.