Antiferromagnetic resonances in twinned EuFe$_2$As$_2$ single crystal.

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In this work, we report ferromagnetic resonance spectroscopy of EuFe$_2$As$_2$ single crystals. We observe ferromagnetic resonance responses, which are attributed to antiferromagnetic resonances of Eu sub-lattice with orthorhombic crystal structure and with different orientations of twin domains relative to the external field. We confirm validity of the recently-proposed spin Hamiltonian with anisotropic Eu-Eu exchange interaction and biquadratic Eu-Fe exchange interaction.

I. INTRODUCTION

The discovery of the iron pnictide high temperature superconductors has been one of the most striking discoveries in recent years in condensed-matter physics. In this class of materials, intriguing properties were recently found in the subclass of compounds originating from the parent EuFe$_2$As$_2$ $^{[1]}$. Superconductivity in EuFe$_2$As$_2$-based ferromagnetic superconductors emerges by doping it with phosphorus $^{[11]}$, or substituting europium layers with rubidium $^{[15-21]}$. In these materials the Fe 3d orbitals exhibit a dual itinerant-localized magnetism, and, simultaneously, participate in superconducting pairing. When it comes to the interplay between the superconductivity and the ferromagnetism, the studies are mainly focused on their superconducting properties and on the physical origin behind the emergence of superconductivity. In case of EuFeAs-based ferromagnetic superconductors the coexistence is considered between magnetic ordering of Eu$^{2+}$ ions with large spin number $S = 7/2$ and superconducting ordering of Fe-3d electrons.

The EuFe$_2$As$_2$ compound itself is rich in various magnetic phenomena. At about 190 K the crystal structure of EuFe$_2$As$_2$ undergoes the tetragonal-to-orthorhombic phase transition $^{[1,2,6]}$, accompanied by the spin density wave antiferromagnetic transition in Fe sub-lattice. The direction of spins in the spin density wave is locked along the longer $a$ crystal axis of the orthorhombic structure (see Fig. 1). At about 20 K the Eu subsystem undergoes the A-type antiferromagnetic transition $^{[2,6,8]}$. The orthorhombic crystal structure is naturally subjected to twinning, but also to magnetostriction due to the movement of twin boundaries in response to changes of the magnetic field and magnetization of Eu sub-lattice $^{[6,8]}$. The latter indicates Eu-Fe exchange interaction. This relocation of twin boundaries is one of the main obstructions for studies of magnetic ordering in EuFe$_2$As$_2$ with magnetization measurements: upon magnetization the variation in fraction of differently oriented twin domains additionally impacts the magnetization. Only recently an adequate microscopic form of magnetic interactions in EuFe$_2$As$_2$ was established $^{[7,8]}$. It includes the anisotropic Eu-Eu exchange interaction, bi-quadratic Eu-Fe exchange interaction, and implies the spin-flip transition in A-type antiferromagnetic Eu sub-lattice when the magnetic field is applied along the $a$ crystal axis. Metamagnetic transitions in EuFe$_2$As$_2$ $^{[2,6,8]}$ are developed due to magnetization of twin domains with the $\pi/2$ difference in their mutual orientation.

FIG. 1. Magnetic crystal structure of EuFe$_2$As$_2$ (made using VESTA software). The crystal structure of EuFe$_2$As$_2$ is orthorhombic with the space group $Fmmm$ $^{[8]}$. Fe spin sub-lattice is in the spin density wave antiferromagnetic state aligned with the $a$ axis. Eu spin sub-lattice is in the A-type antiferromagnetic state.

In this work, we consider magnetization dynamics in single crystal EuFe$_2$As$_2$. In general, ferromagnetic resonance (FMR) measurements are an ultimate tool for testing interlayer exchange interactions in various antiferromagnets $^{[22,24]}$. In addition, FMR studies are free
from the twinning problem, since the ratio of differently oriented twin domains impact the intensity but not the position of resonance lines. By observing and analysing antiferromagnetic resonance spectral lines we have found that the FMR spectrum confirms the validity of the 3D-expanded version of the spin Hamiltonian proposed in Ref. [3].

II. EXPERIMENTAL DETAILS

EuFe$_2$As$_2$ single crystals were grown using the self-flux method, by analogy with previous works [25, 26]. The initial high purity components of phase homogeneous EuAs (99.95% Eu + 99.9999% As) obtained by high-pressure technique, and preliminary synthesized precursor Fe$_2$As (99.98% Fe+99.9999% As) were mixed with a 1:6 molar ratio. The mixture in an alumina crucible was sealed in a niobium tube under residual argon pressure. The sealed container was loaded into a tube furnace with an argon atmosphere to prevent niobium oxidation. Then, the furnace was heated up to 1250°C, held at this temperature for 24 h to homogenize melting, cooled down to 900°C at a rate of 2°C/h, and then cooled down to room temperature inside the furnace. Finally, crystals were collected from the crucible in an argon glove box. Visually, as-grown bulk crystals demonstrate well-defined layered structure and their pliability for cleavage and exfoliation along the layering direction only. XRD studies confirm alignment of $ab$ crystal planes within the layers, and orientation of $c$ crystal axis across the layers. Samples for ferromagnetic resonance spectroscopy were obtained by cleavage of as-synthesized bulk crystals. Cleaved EuFe$_2$As$_2$ samples were of a few mm in size along $ab$ crystal planes, and about 50 μm thick along the $c$ crystal axis, which ensured the “thin film” geometry with defined crystal orientation.

Ferromagnetic resonance spectroscopy was performed using the VNA-FMR flip-chip approach [27, 28]. Cleaved EuFe$_2$As$_2$ sample was glued on top of the transmission line of coplanar waveguide. The waveguide with impedance 50 Ohm and the width of the transmission line 0.5 mm is patterned on a Arlon AD1000 copper board equipped with SMP rf connectors. The board is gradually reduced and in some nonlinear dependence on magnetic field, corresponding to paramagnetic resonance of Eu spins. Figure 2 shows the representative example of the spectrum at $T = 20$ K. The field slope of the paramagnetic resonance at 20 K $f_r/\mu_0 H \approx 36.6$ GHz/T is slightly higher than the gyromagnetic ratio of free electrons 28 GHz/T. In addition, the resonance line shows some deviation from the linear behaviour. These effects are attributed to the residual susceptibility of the paramagnetic phase in vicinity to the Curie temperature and should be understood as follows. The magnetization of the paramagnetic phase is proportional to the applied field $M = \chi(T, H) H$. In the thin-film geometry the resonance frequency of the paramagnetic phase is still provided by the Kittel formula $2\pi f = \gamma \sqrt{H(H + M)} = \gamma H \sqrt{1 + \chi(T, H)}$. At temperatures slightly above the Curie temperature, magnetization $\chi(T, H)H$ is comparable to the saturation magnetization at high fields and show nonlinear dependence on $H$. These factors result in larger slope of the linear fit and in some nonlinearity of the resonance line, which are observed in Fig. 2. At higher temperatures $\chi(T, H)$ is gradually reduced and the resonance line approaches the conventional paramagnetic one, which is observed at 25 K and 30 K (see supplementary). Figure 2 shows the cross-section of the spectrum $S_{21}(H)$ at $f = 17.5$ GHz, which contains a single resonance peak, and its fit with the complex susceptibility.

The spin configuration of Eu and Fe subsystems in EuFe$_2$As$_2$ and the twinning problem were studied extensively in a number of previous works with neutron scattering and XMCD measurements. As a consensus, it is shown that at low temperature Fe sub-lattice is in the spin density wave antiferromagnetic state aligned

III. RESULTS AND DISCUSSIONS

Figure 2 shows FMR absorption spectra of EuFe$_2$As$_2$ sample measured at magnetic field applied in-plane along $ab$ layers at $T = 5$ K and 20 K. At 5 K (Fig. 2a) the spectrum contains three absorption features (encircled with red dashed lines): (i) a resonance line at $0 < \mu_0 H \lesssim 0.5$ T and $10 < f < 23$ GHz with a negative-slope linear field dependence, referred to as line I; (ii) a weaker resonance line at $\mu_0 H \gtrsim 0.7$ T and $18 < f < 22$ GHz, which also has approximately linear field dependence with a negative slope, referred to as line II; and (iii) an absorption “patch” at $0.55 < \mu_0 H \lesssim 0.7$ T and $f > 20$ GHz, referred to as the absorption feature III. A spectral line with the negative field-slope is commonly attributed to an antiferromagnetic resonance response. Cross-sections $S_{21}(H)$ of the spectrum at 5 K and at selected frequencies are shown in Fig. 2b. The $S_{21}(H)$ curves clearly indicate absorption peaks of resonance lines I and II. Derivation of FMR frequency dependence on applied magnetic field $f_r(H)$ was performed by fitting $S_{21}(H)$ curves with the complex resonant susceptibility [28].
with the longer side of orthorhombic lattice, while Eu sub-lattice has the A-type antiferromagnetic order (see Fig. 1). Importantly, Eu-Fe exchange interaction results in anisotropic Eu-Eu exchange interaction and in development of the easy axis along the direction of the spin density wave \((a\text{-direction})\) due to bi-quadratic Eu-Fe exchange. The total free energy of the spin configuration in a unit cell of Eu layers is [8]

\[
F = 2(J + W)e_{1x}e_{2x} + 2(J - W)e_{1y}e_{2y} + 2Je_{1z}e_{2z} + 8K_u \sum_{i=1}^{2} e_{i}^2 + K_u \sum_{i=1}^{2} e_{i}^2 - M_s \sum_{i=1}^{2} e_{i} \hat{H},
\]

where \((e_{1x}, e_{1y}, e_{1z})\) is the unit vector of ferromagnetic moment of the Eu atomic layer in spherical coordinates \(e = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}\), \([\hat{x}, \hat{y}, \hat{z}]\) axes are aligned with \([a, b, c]\) crystal axes in Fig. 1 respectively, the first three terms are the exchange interaction terms, which are anisotropic in \(x\) and \(y\) directions by the parameter \(W\), the forth term is the bi-quadratic Eu-Fe exchange interaction in a form of the \(x\)-axis uniaxial anisotropy, the fifth term is the \(z\)-axis uniaxial anisotropy, and the last term is the Zeeman energy with the external field \(\hat{H}\), which is applied in \(ab\) plane at the angle \(\phi_H\) with respect to the \(a\)-axis. In comparison to Ref. [8], two terms \([2J e_{1x}e_{2y}]\) and \([K_u \sum_{i=1}^{2} e_{i}^2]\) are added to complete the 3D representation of the free energy, while the Eu-Fe exchange interaction is redefined in the \(x\)-axis uniaxial form.

Following Ref. [8], exchange and anisotropy parameters of the free energy can be derived from saturation fields of the canted spin state and of the spin-flip transition as follows. When magnetic field is applied along the \(b\) crystal axis, magnetization of Eu occurs via spin canting (i.e., via the spin-flip phase) and the saturation field of the spin-flip phase is \(H_{s}^{\text{sat}} = (4J + 16K_u)/M_s\). When magnetic field is applied along the \(a\) crystal axis, magnetization saturation occurs via abrupt spin-flip transition and the saturation field (i.e., the spin-flip field) is \(H_{a}^{\text{sat}} = 2(J + W)/M_s\). Notice that counter-intuitively
$H_{s}^{\text{sat}}$ and $H_{b}^{\text{sat}}$ do not match each other even in the isotropic case of $W = 0$, $K_{a} = 0$. This is the consequence of the spin-flip as the dominating magnetization process for the corresponding magnetic orientation $\hat{s}$. The condition for the spin-flip transition is $J/(8K_{a} + W) < 1$. When magnetic field is applied at 45° with respect to $a$ or $b$ direction, the saturation field is $H_{s}^{\text{sat}} = 4J/M_{s}$. By expanding the treatment to the 3D case, the saturation field of the canting spin state for field orientation along the $c$ axis is $H_{b}^{\text{sat}} = (4J + 2W + 16K_{a} + 2K_{c})/M_{s}$.

The dependence of orientations of Eu magnetic moments on the magnetic field can be derived numerically by minimising the energy in Eq. (1) with predefined anisotropy and exchange parameters. By knowing orientations of Eu magnetic moments, ferromagnetic resonance of Eu can be derived using the Suhl-Smit-Beljers approach [30, 31] extended for the case of magnetization dynamics in coupled magnetic multilayers [24, 32–34]. With this approach the following set of equations of motion for magnetization vector in each Eu layer defines the collective dispersion of the spin system with orientation along $ab$ planes ($\theta_i = \pi/2$):

$$\frac{\omega M_{s}}{\gamma} \begin{bmatrix} \delta \theta_1 \\ \delta \theta_2 \\ \delta \phi_1 \\ \delta \phi_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & F_{\phi_1\phi_1} & F_{\phi_1\phi_2} \\ 0 & 0 & F_{\phi_2\phi_1} & F_{\phi_2\phi_2} \\ -F_{\phi_1\phi_1} & -F_{\phi_2\phi_2} & 0 & 0 \\ -F_{\phi_1\phi_2} & -F_{\phi_2\phi_1} & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta \theta_1 \\ \delta \theta_2 \\ \delta \phi_1 \\ \delta \phi_2 \end{bmatrix},$$

(2)

where $\delta \theta_i$ and $\delta \phi_i$ are components of small deviations of magnetization vector in spherical coordinates, $F_{\phi_i\phi_j}$ are corresponding second-order partial derivatives of the free energy (Eq. (1)), $\omega$ is the eigen-frequency of magnetization precession, and $\gamma = 28$ GHz/T is the gyromagnetic ratio. Diagonal terms $F_{\phi_i\phi_i} = 0$ in Eq. (2) due to the in-plane configuration of magnetization ($\theta_i = \pi/2$). The expression $\sum \cos (\phi_i - \phi_H) \delta \phi_i$ corresponds to the dynamic susceptibility of the resonance.

Figure 3 collects experimental and theoretical dependencies of the ferromagnetic resonance frequency on the magnetic field $f_r(H)$. Black lines show theoretical data for the A-domain with $\phi_H = 0$. Red lines show theoretical data for the B-domain with $\phi_H = \pi/2$. Solid lines show either individual resonances of Eu sub-lattices, as in case of $\phi_H = 0$ and $\mu_0H < 0.5$, or the collective acoustic response. Dashed lines show the collective optical response. Arrows indicate transition fields $H_{a}^{\text{sat}}$ and $H_{b}^{\text{sat}}$. Black squared dots show experimental $f_r(H)$ lines derived from the spectrum at 5 K. Error bars indicate the line-width of experimental resonance lines $\Delta H \approx 0.17$ T and $\Delta f \approx 4.5$ GHz for line I, and $\Delta H \approx 0.13$ T and $\Delta f \approx 4$ GHz for line II. Blue short-dashed line indicates the accessible range of the experimental setup. Pictograms illustrate spin configurations in twinned domains at different fields. A-domains (shown with blue) correspond to domains with the spin density wave axis ($a$-axis) aligned with the magnetic field. B-domains (shown with red) correspond to domains with the spin density wave axis ($a$-axis) aligned perpendicular to the magnetic field.

Figure 3. The plot shows experimental and theoretical dependencies of the ferromagnetic resonance frequency on the magnetic field $f_r(H)$. Black lines show theoretical data for the A-domain with $\phi_H = 0$. Red lines show theoretical data for the B-domain with $\phi_H = \pi/2$. Solid lines show either individual resonances of Eu sub-lattices, as in case of $\phi_H = 0$ and $\mu_0H < 0.5$, or the collective acoustic response. Dashed lines show the collective optical response. Arrows indicate transition fields $H_{a}^{\text{sat}}$ and $H_{b}^{\text{sat}}$. Black squared dots show experimental $f_r(H)$ lines derived from the spectrum at 5 K. Error bars indicate the line-width of experimental resonance lines $\Delta H \approx 0.17$ T and $\Delta f \approx 4.5$ GHz for line I, and $\Delta H \approx 0.13$ T and $\Delta f \approx 4$ GHz for line II. Blue short-dashed line indicates the accessible range of the experimental setup. Pictograms illustrate spin configurations in twinned domains at different fields. A-domains (shown with blue) correspond to domains with the spin density wave axis ($a$-axis) aligned with the magnetic field. B-domains (shown with red) correspond to domains with the spin density wave axis ($a$-axis) aligned perpendicular to the magnetic field.
2W/Mₐ ≈ 0.1 – 0.2 T; \( H_{sat}^a \approx 0.45 – 0.55 \) T; \( H_{sat}^b = \frac{(4J + 16K_a)}{M_s} \approx 1.15 – 1.25 \) T; \( K_a/M_s \approx 0.2 – 0.3 \) T; \( |\phi_H| < 5^\circ \). The large width of resonance lines and limited experiential range did not allow to perform more accurate optimisation of parameters. Solid and dashed lines in Fig. 3 shows \( f_r(H) \) obtained using Eqs. 1 and 2 and the following set of parameters: \( 4J/M_s \approx 0.8 \) T; \( 2W/M_s \approx 0.1 \) T; \( H_{sat}^a \approx 0.5 \) T; \( H_{sat}^b = \frac{(4J + 16K_a)}{M_s} \approx 1.2 \) T; \( K_a/M_s \approx 0.25 \) T; \( |\phi_H| < 5^\circ \). According to Fig. 3 the spectral line I corresponds to the resonance of Eu spins aligned against the external field in the domain having the angle \( \phi_H = 0 \) with the external field. The spectral line II corresponds to the optical antiferromagnetic response in the domain having the angle \( \phi_H = \pi/2 \) with the external field. Its optical origin explains the low intensity in comparison with line I.

![Absorption spectra](image)

**FIG. 4.** a) FMR absorption spectra \( S_{21}(f, H) \) of EuFe₂As₂ measured at \( T = 13 \) K. Magnetic field is applied in-plane along ab crystal planes. Red dots show experimental resonance curves \( f_r(H) \) obtained by fitting spectral lines. b) Cross-section \( S_{21}(H) \) of the spectrum at \( T = 13 \) K at \( f = 25 \) GHz. Solid lines in (b) show the fit of the resonant feature.

The spectral feature III in Figs. 3 and 4 may be attributed to the optical antiferromagnetic response in the same B-domain. In this case the change in the line intensity is the signature of the twin domain wall relocation when the fraction of these domains reduces with the magnetic field. Alternatively, the spectral feature III may be a trace of the acoustic mode of the A-domain with \( \phi_H = 0 \) and \( H > H_{sat}^a \). The origin of the spectral feature III can be established by studying temperature dependence of the spectrum. Upon increasing the measurement temperature all spectral lines shift to lower frequencies, while the transition fields decrease (see supplementary). Figure 3 shows FMR absorption spectrum of EuFe₂As₂ sample measured at magnetic field applied in-plane along ab layers at \( T = 13 \) K. The spectrum contains the same three absorption features (experimental \( f_r(H) \) dependencies are shown with red dots). The resonance line I at \( 0.2 < \mu_0 H < 0.4 \) T and \( 10 < f < 15 \) GHz corresponds to resonance of Eu spins aligned against the external field in the A-domain having the angle \( \phi_H = 0 \) with the external field (see schematic images in Fig. 3). A weak resonance line II at \( 0.7 < \mu_0 H < 0.8 \) T and \( 12 < f < 18 \) GHz corresponds to the optical antiferromagnetic response in the B-domain having the angle \( \phi_H = \pi/2 \) with the external field. The spectral feature III at \( T = 5 \) K (Fig. 4) is transformed at \( T = 13 \) K into a clearly distinguishable resonance line at \( 0.45 \lesssim \mu_0 H \lesssim 0.7 \) T and \( 18 < f < 26 \) GHz with positive-slope line dependence \( f_r(H) \), thus, manifesting the acoustic mode of A-domains with \( \phi_H = 0 \) and \( H > H_{sat}^a \). Lines I and III indicate that the spin-flip field at \( T = 13 \) K is reduced to \( H_{sat}^a \approx 0.4 \) T as compared to \( H_{sat}^a \approx 0.5 \) T at 5 K. Figure 4 shows the cross-section of the spectrum \( S_{21}(H) \) at \( f = 25 \) GHz. The cross-section indicates a drop of the transmission at \( \mu_0 H \approx 0.4 \) T. This drop is attributed to the spin-flip transition of A-domains but is not related to a spin resonance process. At \( \mu_0 H > 0.4 \) T magnetization of A-domains is changed step-wise, which result in corresponding changes of the impedance of the transmission line and, consequently, in its transmission characteristics regardless a resonance process. In addition, the curve \( S_{21}(H) \) shows a resonance peak III at \( \mu_0 H \approx 0.58 \) T. The fit of resonance peaks with the complex susceptibility allowed to derive the resonance line \( f_r(H) \), which is shown in Fig. 4 with red dots.

The overall correspondence between experimental and theoretical lines in Fig. 3 and established nature of all lines in Figs. 3 and 4 confirm the validity of the free energy relation in Eq. 1 with the anisotropic Eu-Eu exchange interaction and bi-quadratic Eu-Fe exchange interaction for EuFe₂As₂ compound together with the domain twinning concept of its orthorhombic crystal structure.

Once the validity of the Hamiltonian and the origin of all three lines are established it is instructive to consider resonance properties of EuFe₂As₂ in more details. First, it can be noticed that at zero field in Fig. 3 resonance lines are split by \( \Delta f_r \approx 0.5 \) GHz. In general, for two-sublattice antiferromagnets the zero-filed split occurs due to the two-axes anisotropy. From Eq. 2 at \( H = 0 \) it...
can be derived that the split in FMR frequency is set by the difference between two eigen frequencies given by expressions

\[
\left( \frac{2\pi f_r}{\mu_0 \gamma} \right)^2 = (2W + 16K_a + 2K_u)(4J + 16K_a),
\]

\[
\left( \frac{2\pi f_r}{\mu_0 \gamma} \right)^2 = (4J + 2W + 16K_a + 2K_u)(4W + 16K_a).
\]

As follows from Eq. 3 in the case of EuFe\(_2\)As\(_2\) the width of the split \(\Delta f_r\) is also affected by the anisotropy in the exchange interaction. In the isotropic case, \(W = 0\) and \(K_u = 0\), both expressions relax to the known textbook split-less expression \([23, 35]\). However, it should be noticed that \(\Delta f_r\) is by far smaller that the linewidth of resonance lines, and, thus, can not be verified directly for EuFe\(_2\)As\(_2\).

Next, we consider the resonance of magnetically-saturated A- and B-domains. In terms of Eq. 4 by setting \(\epsilon_1' = \epsilon_2'\) the Suhl-Smit-Beljers approach yields for a single magnetic layer

\[
\left( \frac{2\pi f_r}{\mu_0 \gamma} \right)^2 = (H + 16K_a - 4W)(H + 16K_a - 2W + 2K_u)
\]

for the higher-frequency acoustic mode of the A-domain at \(H > H_{sat}^b\), and

\[
\left( \frac{2\pi f_r}{\mu_0 \gamma} \right)^2 = (H - 16K_a + 4W)(H + 2W + 2K_u)
\]

for the higher-frequency acoustic mode of the B-domain at \(H > H_{sat}^a\). Figure 5 shows theoretical dependencies of the ferromagnetic resonance frequency on the magnetic field \(f_r(H)\) obtained numerically with Eqs. 12 using the same parameters as in Fig. 3 and analytically with Eqs. 15. The consistency between corresponding resonance lines confirms the validity of numerical studies. Interestingly, the exchange anisotropy parameter \(W\) enters both expressions, which can be used additionally in FMR determination of magnetic properties of complex antiferromagnets.

IV. CONCLUSION

In conclusion, in this work we report ferromagnetic resonance spectroscopy of EuFe\(_2\)As\(_2\) single crystals. The spectrum reveals several resonant features attributed to antiferromagnetic resonances of Eu sublattice. By employing the recently proposed spin Hamiltonian with anisotropic Eu-Eu exchange interaction and bi-quadratic Eu-Fe exchange interaction, the spectral features have been identified and attributed to antiferromagnetic and collective resonances of Eu layers in orthorhombic twinned crystal with different orientation of twin domains with respect to the external field. The obtained magnetic parameters are quantitatively consistent with those reported previously, thus, confirming the complex biquadratic Hamiltonian for Eu spins in EuFe\(_2\)As\(_2\) proposed earlier.

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[1] Z. Ren, Z. Zhu, S. Jiang, X. Xu, Q. Tao, C. Wang, C. Feng, G. Cao, and Z. Xu, Phys. Rev. B 78, 052501 (2008).

[2] H. S. Jeevan, Z. Hossain, D. Kasinathan, H. Rosner, C. Geibel, and P. Gegenwart, Phys. Rev. B 78, 052502 (2008).
[3] S. Jiang, Y. Luo, Z. Ren, Z. Zhu, C. Wang, X. Xu, Q. Tao, G. Cao, and Z. Xu, New J. Phys. 11, 025007 (2009).
[4] Y. Xiao, Y. Su, M. Meven, R. Mittal, C. M. N. Kumar, T. Chatterji, S. Price, J. Persson, N. Kumar, S. K. Dhar, et al., Phys. Rev. B 80, 174424 (2009).
[5] Y. Xiao, Y. Su, W. Schmidt, K. Schmalzl, C. M. N. Kumar, S. Price, T. Chatterji, R. Mittal, L. J. Chang, S. Nandi, et al., Phys. Rev. B 81, 220406 (2010).
[6] S. Zapf, C. Stingl, K. Post, J. Maiwald, N. Bach, I. Pietsch, D. Neubauer, A. Lohle, C. Clauss, S. Jiang, et al., Phys. Rev. Lett. 113, 227001 (2014).
[7] J. Maiwald, I. I. Mazin, and P. Gegenwart, Phys. Rev. X 8, 011011 (2018).
[8] J. J. Sanchez, G. Fabbris, Y. Choi, Y. Shi, P. Malinowski, S. Pandey, J. Liu, I. I. Mazin, J.-W. Kim, P. Ryan, et al., Phys. Rev. B 104, 104413 (2021).
[9] Z. Ren et al., Phys. Rev. Lett. 102, 137002 (2009).
[10] G. Cao, S. Xu, Z. Jiang, C. Feng, and Z. Xu, Journal of Physics: Condensed Matter 23, 464204 (2011).
[11] H. S. Jeevan et al., Phys. Rev. B 83, 054511 (2011).
[12] S. Nandi et al., Phys. Rev. B 89, 014512 (2014).
[13] V. S. Stolyarov et al., Sci. Adv. 4, eaat1061 (2018).
[14] S. Grebenchuk et al., Phys. Rev. B 102, 144501 (2020).
[15] Y. Liu, Y.-B. Liu, Z.-T. Tang, H. Jiang, Z.-C. Wang, A. Ablimit, W.-H. Jiao, Q. Tao, C.-M. Feng, Z.-A. Xu, et al., Phys. Rev. B 93, 214503 (2016).
[16] Y. Liu, Y.-B. Liu, Y.-L. Yu, Q. Tao, C.-M. Feng, and G.-H. Cao, Phys. Rev. B 96, 224510 (2017).
[17] M. P. Smylie, K. Willa, J.-K. Bao, K. Ryan, Z. Islam, H. Claus, Y. Simsek, Z. Diao, A. Rydh, A. E. Koshelev, et al., Phys. Rev. B 98, 014503 (2018).
[18] T. K. Kim, K. S. Pervakov, D. V. Evtushinsky, S. W. Jung, G. Poelchen, K. Kummer, V. A. Vlasenko, A. V. Sadakov, A. S. Usoltsev, V. M. Pudalov, et al., Phys. Rev. B 103, 174517 (2021).
[19] T. Kim, K. Pervakov, V. Vlasenko, A. Sadakov, A. Usoltsev, D. Evtushinsky, S. Jung, G. Poelchen, K. Kummer, D. Roditchev, et al., Phys. Usp. (2021).
[20] K. Iida, Y. Nagai, S. Ishida, M. Ishikado, N. Murai, A. D. Christianson, H. Yoshida, Y. Inamura, H. Nakamura, A. Nakao, et al., Phys. Rev. B 100, 014506 (2019).
[21] S. Ishida, D. Kagerbauer, S. Holleis, K. Iida, K. Munakata, A. Nakao, A. Iyo, H. Ogino, K. Kawashima, M. Eisterer, et al., PNAS 118, e2101101118 (2021).
[22] A. N. Bogdanov, A. V. Zhuravlev, and U. K. Rößler, Phys. Rev. B 103, 174517 (2021).
[23] S. M. Rezende, A. Azvedo, and R. L. Rodríguez-Suárez, J. Appl. Phys. 126, 151101 (2019).
[24] I. Golovchanskiy and V. Stolyarov, J. Appl. Phys. 131, 053901 (2022).
[25] K. S. Pervakov, V. A. Vlasenko, E. P. Khrblov, A. Zalesski, V. M. Pudalov, and Y. F. Eltsev, Supercond. Sci. Technol. 26, 015008 (2013).
[26] V. Vlasenko, K. Pervakov, and S. Gavrilkin, Supercond. Sci. Technol. 33, 084009 (2020).
[27] I. Neudecker, G. Woltersdorf, B. Heinrich, T. Okuno, G. Gubbiotti, and C.H. Back, J. Mag. Mag. Mater. 307, 148 (2006).
[28] S. S. Kalarickal, P. Krivosik, M. Wu, C. E. Patton, M. L. Schneider, P. Kabos, T. J. Silva, and J. P. Nibarger, J. Appl. Phys. 99, 093909 (2006).
[29] D. MacNeill, J. T. Hou, D. R. Klein, P. Zhang, P. Jarillo-Herrero, and L. Liu, Phys. Rev. Lett. 123, 047204 (2021).
[30] H. Suhl, Phys. Rev. 97, 555 (1955).
[31] J. Smit and H. G. Beljers, Philips Res. Rep. 10, 113 (1955).
[32] Z. Zhang, L. Zhou, P. E. Wigen, and K. Ounadjela, Phys. Rev. B 50, 6094 (1994).
[33] D. S. Schmooly and J. M. Barandiaran, J. Phys.: Condens. Matter 10, 10679 (1998).
[34] J. Lindner and K. Baberschke, J. Phys.: Condens. Matter 15, S465 (2003).
[35] A. G. Gurevich and G. A. Melkov, eds., Magnetization Oscillations and Waves (CRC Press, 1996).