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The strongly correlated insulator Ca$_2$RuO$_4$ is considered as a paradigmatic realization of both spin-orbital physics and a band-Mott insulating phase, characterized by orbitally selective coexistence of a band and a Mott gap. We present a high resolution oxygen K-edge resonant inelastic x-ray scattering study of the antiferromagnetic Mott insulating state of Ca$_2$RuO$_4$. A set of low-energy (about 80 and 400 meV) and high-energy (about 1.3 and 2.2 eV) excitations are reported, which show strong incident light polarization dependence. Our results strongly support a spin-orbit coupled band-Mott scenario and explore in detail the nature of its exotic excitations. Guided by theoretical modeling, we interpret the low-energy excitations as a result of composite spin-orbital excitations. Their nature unveils the intricate interplay of crystal-field splitting and spin-orbit coupling in the band-Mott scenario. The high-energy excitations correspond to intra-atomic singlet-triplet transitions at an energy scale set by Hund’s coupling. Our findings give a unifying picture of the spin and orbital excitations in the band-Mott insulator Ca$_2$RuO$_4$.

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I. INTRODUCTION

Spin-orbit coupling (SOC) is a central thread in the search for novel quantum material physics [1]. A particularly promising avenue is the combination of SOC and strong electron correlations in multi-orbital systems. This scenario is realized in heavy transition metal oxides composed of 4$d$ and 5$d$ elements. Iridium oxides (iridates) such as Sr$_2$IrO$_4$ are prime examples of systems where SOC plays a defining role in shaping the Mott insulating ground state [2]. In fact, spin-orbit entanglement essentially outplays the effectiveness of the usually influential crystal field $\delta$. Of equal interest is the complex regime where SOC and crystal-field energy scales are comparable. Here, Ca$_2$RuO$_4$ is a topical material that displays a wealth of physical properties. A record-high nonsuperconducting diamagnetic response has, for example, been reported recently [3]. Superconductivity emerges in strained films [4] or upon application of hydrostatic pressure to bulk crystals [5]. Neutron and Raman scattering experiments have demonstrated both phase and amplitude spin-excitation modes consistent with the existence of a spin-orbit exciton [6–8]. Moreover, measurements of the paramagnetic insulating band structure [9] were interpreted in favor of an orbitally differentiated band-Mott insulating ground state [10,11]. This rich phenomenology of Ca$_2$RuO$_4$ is a manifestation of the interplay between multiple energy scales—specifically, the Coulomb interaction $U$, Hund’s coupling $J_H$, the crystal-field splitting $\delta$, and SOC $\lambda$. In particular, a...
tendency towards an orbital selective Mott state is expected to be driven by Hund’s coupling [12]. Furthermore, the band-Mott scenario is triggered by a crystal field that renders the $d_{xy}$ orbital band insulating, such that the resulting half-filled $d_{xy}$, $d_{yz}$ band undergoes a conventional Mott transition driven by the Coulomb interaction [11].

The low-energy electronic excitations of Ca$_2$RuO$_4$ have been interpreted within an exciton picture where SOC enters as an important parameter [13]. A similar framework has been applied to layered iridates—with a 5/6-filled $t_{2g}$ shell—where a $J_{\text{eff}} = 1/2$ quasiparticle emerges from strong SOC. The existence of this quasiparticle has been confirmed by detailed resonant inelastic x-ray scattering (RIXS) studies of both spin and orbital excitations [14,15]. For Ca$_2$RuO$_4$, with modest spin-orbit coupling strength, studies of the spin excitations have been interpreted as evidence for a similar composite $J_{\text{eff}} = 1$ quasiparticle [16,17]. However, the full manifold of the low-lying spin-orbital excitations of Ca$_2$RuO$_4$ has not yet been observed.

The possibility to detect Ru $d$-orbital excitations through the oxygen $K$ edge [18,19] offers a unique opportunity in the case of ruthenates, where direct $L$-edge RIXS is not yet available for high-resolution measurements. Moreover, spin-orbital excitations are mostly inaccessible to neutron scattering.

Here, we present an oxygen $K$-edge RIXS study of Ca$_2$RuO$_4$ focusing on the magnetically ordered phase. Two low-energy excitations (80 and 400 meV) and two high-energy excitations (1.3 and 2.2 eV) are identified. Light-polarization analysis yields insight to the internal orbital character of these excitations. A detailed analysis of the 400-meV excitation uncovered a weak dispersion, consistent with a propagating nature.

In contrast, the high-energy excitations are closely linked to Hund’s coupling energy scale $J_{\text{H}}$. The excitations reported here on Ca$_2$RuO$_4$ are unique features of (1) a band-Mott insulating phase controlled by Hund’s coupling and Coulomb interactions, and (2) a composite spin-orbital excitation resulting from SOC. Hence, our results give experimental support for Ca$_2$RuO$_4$ being in a spin-orbit-coupled band-Mott insulating phase. Thus, it provides an experimental unification of the band-Mott [9,11] and van Vleck-type Mott [16,20] insulator scenarios.

II. METHODS

High-quality single crystals of Ca$_2$RuO$_4$ were grown using the floating zone techniques [21,22]. X-ray absorption spectroscopy (XAS) and RIXS [23] were carried out at the ADRESS beamline [24,25] at the Swiss Light Source (SLS). The scattering geometry is indicated in Fig. 1(a). A fixed angle of 130° between incident light and scattered light was used. In-plane momentum is varied by controlling the incident photon angle $\theta$ shown in Fig. 1(a). Grazing and normal incidence conditions refers to $\theta \approx 90^\circ$ and $0^\circ$, respectively. Linear vertical (LV) and horizontal (LH) light polarizations were used to probe the oxygen $K$ edge at which an energy resolution of 29 meV or better (half width

![FIG. 1. (a) RIXS geometry with respect to the crystal lattice of Ca$_2$RuO$_4$ is displayed schematically. Ruthenium and oxygen sites are shown with filled green and blue circles, respectively. The variable incident angle $\theta$ is defined with respect to the RuO$_2$ and apical oxygen planes. Using LV and LH polarized light, for different $\theta$, sensitivity to either oxygen $p_x$, $p_y$, or $p_z$ orbitals can be obtained. These oxygen orbitals in turn hybridize with different unoccupied $t_{2g}$ and $e_g$ states on the ruthenium site. (b–d) XAS and RIXS spectra recorded with linear horizontal light for near grazing and normal incident light conditions as indicated. (b) Background-subtracted x-ray absorption spectra recorded with settings that optimize either the apical or planar oxygen $K$-edge resonances as indicated by the dashed vertical lines. Panels (c) and (d) display RIXS spectra measured at the planar and apical oxygen $K$ edges.](image-url)
at half maximum) was obtained. Despite the orthorhombic low-temperature (S-Pbca) crystal structure of Ca$_2$RuO$_4$, we indicate momenta $Q = (h, k, l)$ using tetragonal notation in reciprocal lattice units, with $a \approx b = 3.84 \text{ Å}$ and $c \approx 11.95 \text{ Å}$. Furthermore, since Ca$_2$RuO$_4$ is a quasi-two-dimensional system, we consider only the planar component $Q_{\parallel} = (h, k)$ involved in the RIXS process. Throughout this work, elastic scattering is modeled by using a Voigt line shape, allowing subtraction of this component. The presented data are collected at $T = 16 \text{ K}$ unless otherwise indicated.

### III. RESULTS

XAS spectra recorded with LH light polarization near normal and grazing incidence conditions are shown in Fig. 1(b). Good agreement with previous published XAS experiments [26–28] is found when overlap in temperature, light polarization, and incident angle allows for a comparison. As is common in single-layer perovskite structured transition metal oxide materials [26,27,29,30], the planar oxygen absorption resonance is found to be 1–2 eV above that of the apical site. As previously reported [26,27,31], the apical and planar oxygen K-edge peaks are found at about 529.1 eV and 529.8 eV [see Fig. 1(b)]. These resonances stem from hybridization of the oxygen $p$-bands with the ruthenium $t_{2g}$ states, whereas the resonances at higher photon energies are related to hybridization with unoccupied $e_g$ states.

In Fig. 2, four RIXS distinct excitations—labeled $A$, $B$, $C$, and $D$—with approximate energy losses of 0.08, 0.4, 1.3, and 2.4 eV, are displayed in addition to elastic scattering and $dd$ excitations in the 3–5-eV range [see Figs. 1(c) and 1(d)]. Only the $B$ excitation (at about 0.4 eV) has previously been discussed in Ref. [31]. The amplitudes of these excitations strongly depend on incident light angle and polarization.

![FIG. 2. Planar RIXS spectra, with elastic scattering subtracted and recorded with LH and LV light polarization for incident angle (momentum transfer) as indicated. Vertical arrows indicate the four excitations labeled $A$, $B$, $C$, and $D$. For clarity, the spectra are given an arbitrary vertical shift.](image)

![FIG. 3. Polarization dependence of the RIXS spectra versus incident photon energy. (a,b) RIXS response, in false intensity scale, as a function of energy loss and incident photon energy of LH and LV light polarization for the grazing incidence condition, as indicated. Horizontal dashed lines show the positions of the apical and planar resonances obtained from XAS. (c,d) RIXS spectra, with the elastic response subtracted, at the apical (blue lines) and planar (red lines) oxygen resonances for the respective light polarizations. (e,f) Calculated RIXS spectra for the planar site with respect to linear horizontal (c) and vertical (d) light polarization (see text for a detailed explanation of the model). Green lines indicate the expected excitations, and the solid red line is obtained by Gaussian convolution to mimic instrumental resolution. A standard deviation of $\sigma = 70 \text{ meV}$ was applied in panels (e) and (f), whereas $\sigma = 7 \text{ meV}$ was used for the inset, which displays a zoom on the lowest excitations at around 40 meV.](image)
These matrix elements are furthermore different on the apical and planar resonances. All four excitations are therefore not necessarily visible in a single spectrum—as in Fig. 2. We start by discussing the two most intense excitations, \( B \) and \( D \). Plotting the photon-energy-dependent RIXS response (Fig. 3) for the grazing incident condition, these two excitations are the most prominent features in the spectra. They are particularly intense on the planar oxygen K-edge resonance for LH polarization. Interestingly, these excitations are virtually "turned off" when the light polarization is switched to LV polarization. The opposite polarization dependence is observed on the apical site, where the excitations are observed for LV and suppressed for LH polarized light. The same light polarization analysis for an incident angle between grazing and normal incidence is shown in Figs. 2 and 4(a) for the planar resonance. It reveals several important insights. (1) The line shape of the \( B \) excitation is strongly dependent on the incident light polarization. In fact, the peak maximum depends on light polarization [Fig. 4(a)]. (2) The \( D \) excitation is stronger for the grazing incidence and generally weaker in the LV channel. By contrast, the \( C \) excitation is more visible with LV polarization (Fig. 2). (3) The same is true for the \( A \) excitation: On the planar resonance, it is barely resolvable with LH light, but it appears clearly in the LV channel. In Fig. 4(c), we demonstrate how the \( A \) excitation appears in both the LH and LV channels on the apical resonance (near normal incidence). (4) The linewidth of the \( A \) excitation is essentially resolution limited and hence much sharper than that of \( B \). The implications of this observation will be discussed in greater detail below.

We now discuss temperature and momentum dependence of the \( A \) and \( B \) excitations. As evident from Fig. 4(c), both the \( A \) and \( B \) excitations persist into the paramagnetic phase. The momentum dependence—along the \((h,0)\) (Ru–O bond) direction—of planar spectra recorded with LH polarization is shown in Fig. 4(b). The peak maximum position, extracted from fitting the derivative of the spectra, reveals a weak momentum dependence, consistent with a dispersive \( B \) sector. The extracted momentum dispersion of the excitation is reported [Fig. 5(b)] with a minimum at the zone center. In comparison, no dispersion of the \( A \) excitation could be resolved within the applied energy resolution. For completeness, the RIXS data are compared with the amplitude spin excitation mode reported by inelastic neutron scattering (INS) [7].

![FIG. 4. (a) Same spectra as in Fig. 2 displayed with emphasis on the low-energy excitations. Solid blue lines are a four-component fit, including a smoothly growing background (gray lines—second-order polynomial form), the 80-meV excitation (purple line—Gaussian line shape), and two modes with damped harmonic oscillator line shape [32–34] labeled \( B_1 \) (yellow) and \( B_2 \) (green) for the excitation at 400 meV. The position and width of \( B_1 \) and \( B_2 \) are assumed to be identical for LV and LH polarization. Peak amplitudes, by contrast, are left as open fit parameters irrespectively of light polarization. (b) RIXS spectra at planar resonance recorded using linear horizontal light polarization as a function in-plane momenta, as indicated. Lines in panels (b) and (c) are guides to the eye. (c) Apical RIXS spectra recorded with LV and LH polarization near normal incidence for temperatures, as indicated. Lines in panels (b) and (c) are guides to the eye. (d) Schematics of low-lying energy levels of an interacting model for a single ruthenium site for spin-orbit coupling \( \lambda \) set to zero (left) and to the physical value in \( \text{Ca}_2\text{RuO}_4 \) (right). With four electrons, one of the orbitals \( d_{xy}, d_{xz}, d_{yz} \) is doubly occupied, and the two singly occupied electrons are in a spin-triplet state. Finite spin-orbit coupling lifts the degeneracies of the two sectors denoted \( \alpha \) and \( \beta \). The character of the doubly occupied orbital is displayed along with a color scale indicating the directional dependence of the total spin \( m_z \) moment.](image)
The exact nature of the Mott insulating state of Ca$_2$RuO$_4$ has long been debated. Different theoretical models have been put forward\[10,11,35–37\]. Some of them suggest that all $t_{2g}$ orbitals are involved in the Mott transition. Other models propose that crystal fields drive the $d_{xy}$ states band insulating, and the Mott physics is induced on the resulting half-filled $dx_z^2/dy_z^2$ bands \[10\]. A recent ARPES study of the paramagnetic Mott insulating state supports this combined band-Mott insulating scenario \[9\]. This conclusion was reached by visual comparison of the measured and calculated spectral functions for different scenarios.

Based on this development, it is interesting to evaluate the implications of the band-Mott scenario on the XAS and RIXS spectra. When the $d_{xy}$ orbital is (almost) completely occupied, it is inaccessible to the XAS processes that require unoccupied states. Therefore, $dx_z^2/dy_z^2$ are the main active $t_{2g}$ states available for absorption. The XAS spectra, shown in Fig. 1(b), are in perfect accordance with this picture. For example, near the grazing incident condition using LH polarization, the core electron is promoted to the $p_z$ oxygen orbital that, at the planar site, hybridizes with $dx_z^2/dy_z^2$. Indeed, a pronounced response is observed at the planar oxygen $K$-edge resonance, whereas the intensity at the apical resonance is strongly suppressed. Further, changing to normal incidence (keeping LH polarization), the core electrons are promoted to the oxygen $p_x$ orbital, which at the planar site, hybridizes with $d_{xy}$ and at the apical site with $dx_z^2/dy_z^2$. As shown in Fig. 1, the XAS response flips to the apical resonance. Our XAS results thus suggest that the unoccupied $t_{2g}$ states have predominant $dx_z^2/dy_z^2$ character.

The intensities of the RIXS spectra naturally follow the polarization dependence of the XAS response. We notice that the two excitations $B$ and $D$ observed at 0.4 eV and 2.2 eV, respectively, are most pronounced near grazing incidence with LH polarization. The core electrons are promoted to the oxygen $p_z$ orbital, which at the planar site, hybridizes with $d_{xy}$ and at the apical site with $d_{z^2}$. As shown in Fig. 1, the XAS response flips to the apical resonance. Our XAS results thus suggest that the unoccupied $t_{2g}$ states have predominant $d_{z^2}$ character.

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of Ca$_2$RuO$_4$. Within the fast collision approximation [23,38], the RIXS cross section for exciting an electron from the oxygen $1s$ level into a $2p_{\alpha}$ level, with $k = x, y, z$, is given by

$$I_{p}^{\alpha} \propto \sum_{i} \sum_{m} |\langle m| \hat{n}_{p_{\alpha}i}^0 |0 \rangle |^2 \delta[a - (E_{m} - E_{0})],$$

(1)

where the operator $\hat{n}_{p_{\alpha}i}^0$ measures the hole density of oxygen $p_{\alpha}$ orbitals on all planar ($p_{\alpha}$) or apical (a) oxygen sites surrounding the ruthenium site $i$, $|0\rangle$ is the ground state with energy $E_{0}$, and the sum $m$ runs over all excited states $|m\rangle$ with energies $E_{m}$.

To discuss the spectra presented in Figs. 1 and 3, we model a cluster of two ruthenium sites connected by one planar oxygen site (see Ref. [39]). The ruthenium-site Hamiltonian consists of three terms: (1) crystal-field splitting $\delta$ between the $d_{xy}$, $d_{xz}$, $d_{yz}$ orbitals, (2) SOC $\lambda$, and (3) the Coulomb interaction, which is expanded into intraorbital and interorbital Hubbard interactions of strengths $U$ and $(U - 5J_{H}/2)$, respectively. Interorbital Hund’s coupling and the pair-hopping term are both of strength $J_{H}$. To evaluate the model, material-specific values $\delta = 0.3$ eV, $\lambda = 0.075$ eV, $U = 2$ eV, and $J_{H} = 0.5$ eV [27,31,40] are used. Similar values of $\delta$, $U$, and $J_{H}$ have been used for DMFT calculations [9] of Ca$_2$RuO$_4$, and the ratio $\delta/(2\lambda) = 2$ is comparable to what was used in modeling the spin-excitation dispersion observed by neutron scattering [7]. We stress that, qualitatively, the model is not very sensitive to the exact set of parameters. Although the ratio of spectral weight between the low- and high-energy excitations for horizontal polarization is different from the data, our results presented in Figs. 3(e) and 3(f) qualitatively reproduce the experimental spectra, in particular, the excitation at about 2.2 eV as well as the polarization dependence of the spectral weight. We point out that the spectral features at about 1 eV and 2 eV arise from single and double singlet-triplet excitations at the ruthenium site with an energy of $2J_{H}$ and $4J_{H}$, respectively. Thus, this provides an explanation for the observed C and D excitations. Such modes are spin-orbit activated when mixing $d^{4}$ with $d^{5}$ or $d^{6}$ states, and they represent the lowest-energy singlet-triplet excitations when the total number of doubly occupied orbitals at the ruthenium sites is held fixed (see Ref. [39]).

To elucidate the nature of the low-energy excitations, we concentrate on the local electronic structure at a single ruthenium site. The low-energy configurations have four electrons ($d^{4}$), one doubly occupied orbital (doublon), and the two other electrons in a spin-triplet state. For $\lambda = 0$, the model has a threefold-degenerate ground-state manifold $\alpha$ with a doublon in the $d_{xy}$ orbital. The lowest-lying excitation sector $\beta$ is sixfold degenerate at energy $E_{\alpha\beta} = \delta$, with the doublon in the $d_{xz}$ and $d_{yz}$ orbitals [see Fig. 4(d)]. Finite spin-orbit coupling has two effects: (i) It lifts the degeneracies of the $\alpha$ and $\beta$ states by introducing a splitting of about $\lambda^{2}/\delta$ and $2\lambda$, respectively, and, crucially, (ii) it mixes the orbital character of the doublon state. The $\beta$ states thus correspond to a spin-orbital excitation. The splitting of $\alpha$ states gives rise to low-energy excitations that have been studied using neutron scattering [7] [reproduced in Fig. 4(b)]. Just as the $\beta$ sector has an expected internal orbital structure, it was recently demonstrated by Raman spectroscopy that the low-energy $\alpha$ sector also consists of multiple excitations. In fact, a Raman study also revealed two excitations around 80 meV and associated them with two-Higgs and two-magnon scattering modes [8]. Although optical 80–100 meV phonon modes are not uncommon in transition metal oxides, the Raman study [8] suggests that our $A$ excitation is of magnetic origin. To this end, we stress that our model spectra shown in Fig. 3(c) display low-energy modes with maximum intensity at about 40 meV. It can be assigned to the amplitude and phase excitations arising from the effective $J_{\text{eff}} = 1$ configurations in the $\alpha$ sector. Our cluster analysis, by construction, does not allow us to obtain multiple amplitude excitations associated with the interacting $J_{\text{eff}} = 1$. However, a two-scattering mode (i.e., near 80 meV) is, in principle, expected and would emerge in a larger cluster calculation, eventually considering the RIXS cross section at the oxygen $K$ edge beyond the fast collision approximation. The predicted 40-meV magnetic mode, observed by neutron scattering, should, in principle, also enter into the RIXS cross section. However, it is not observed in our experiment because of the finite energy resolution.

The broadness of the $B$ excitation and its light polarization dependence may be interpreted as a consequence of the internal structure of the $\beta$ sector. In fact, it is possible to fit the $B$ excitation with two internal levels labeled $B_{1}$ and $B_{2}$. Keeping identical linewidths and fixed peak positions, the fits describe both the light polarization dependence [Fig. 4(a)] and the momentum dependence by fitting the peak amplitudes. In particular, the observed light polarization dependence for a fixed incident angle (momentum transfer) strongly suggests that the $B$ excitation indeed has an internal orbital structure. This structure constitutes a clear difference from the single-exciton excitation found on the strongly spin-orbit coupled Mott insulator Sr$_{2}$IrO$_{4}$ [15].

The internal structure raises the need to clarify whether the observed dispersion of the $B$ excitation is a result of matrix element variation of this internal structure. By varying the incident angle (momentum transfer) with LH polarization, a switch between $p_{z}$ (grazing incidence) and $p_{x}$ (normal incidence) is effectuated. The expected sensitivity to the $p_{z}$ and $p_{x}$ oxygen orbitals is shown in Fig. 5(a). In the same figure, the fitted peak amplitudes of the $B_{1}$ and $B_{2}$ levels are shown. As they vary only weakly with momentum, the matrix element effect does not provide a plausible explanation for the observed dispersion. We thus conclude that the dispersion is intrinsic, which in turn indicates the itinerant nature of this sector.
When charge hopping between ruthenium sites is reinstated, these local spin-orbit excitons can propagate. Indeed, they acquire a dispersion through virtual processes involving $d_{x^2}$ excitations on neighboring ruthenium sites. Within second-order perturbation theory, one obtains an estimate of the bandwidth of the spin-orbital excitation in the range of about 30–40 meV, using $t \sim 0.25–0.3$ eV [11] for the ruthenium intersite hopping and $\delta = 0.28$ eV, $\lambda = 0.075$ eV, $U = 2.2$ eV, and $J_H = 0.4$ eV for the other electronic parameters (see Ref. [39]). It is furthermore expected that excitations in the $\alpha$ sector exhibit a weaker dispersion due to the smaller exchange amplitude between the $J_{eff} = 1$ modes. Our model thus qualitatively account for the fact that the $B$ excitation disperses about 30 meV over half a zone, whereas the $A$ excitation, according to inelastic neutron scattering [7] [see Fig. 5(b)], disperses no more than 20 meV over the entire zone.

V. CONCLUSIONS AND OUTLOOK

In summary, we have carried out a comprehensive oxygen $K$-edge RIXS study of Ca$_2$RuO$_4$. We demonstrate that the strong light polarization dependence of the signal is a direct manifestation of the band-Mott insulating nature of Ca$_2$RuO$_4$. The hybridization between oxygen $p$ and ruthenium $d$ states thus primarily involves the $d_{x^2+y^2}$ orbitals. Although the system has a modest SOC, it is a crucial element to explain our observations. Most importantly, it allows for a distinct set of propagating low-energy (0.4 eV) excitations with a spin-orbital character. The spin-orbit coupling is also relevant for activating the high-energy (about 2.2 eV) nondispersive excitations by the RIXS process, achieved by local conversion of triplet into singlet states. For realistic values of crystal fields, Hund’s coupling $J_H$, Coulomb interaction $U$, and SOC, all salient features of the RIXS spectra were captured with minimal theoretical modeling. Our results demonstrate that Ca$_2$RuO$_4$ is a Mott insulator with a paradigmatic competition between SOC and crystal-field energy scales. Combining RIXS data and theoretical modeling, we unveiled how spin-orbital entangled excitations manifest within a spin-orbital-coupled band-Mott insulator. For future studies, it would be of great interest to further resolve the internal structure of the low-energy excitations. We envision two different pillars of experimental strategies that alone or in combination would allow further insight. (1) As synchrotrons are being upgraded for diffraction limited experiments, flux and resolution at the oxygen $K$ edge will improve. In particular, enhanced energy resolution, in combination with the light polarization analysis put forward here, would allow us to study important information on different orbital characters of these excitations. With gains in energy resolution, the RIXS technique will enter further into the spin-excitation sector. (2) Direct high-resolution RIXS experiments on the ruthenium $L$ edge are another promising avenue.

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