Disentangling Electronic and Magnetic Order in NdNiO$_3$ at Ultrafast Timescales

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Understanding how emergent phases arise from microscopic interactions in quantum materials is of fundamental importance. Long range order can be strongly influenced by cooperative or competing interactions, an important example being lattice and magnetic degrees of freedom operative in numerous materials exhibiting insulator-to-metal transitions (IMTs). Ultrafast x-ray pulses provide a powerful approach to temporally disentangle magnetic and structural dynamics, yielding new insights into the subtleties of cooperative or competitive behavior that influence IMTs. Here we utilize femtosecond soft x-ray pulses to simultaneously probe the magnetic and electronic order following optical excitation in NdNiO$_3$ (NNO), a model nickelate exhibiting structural and magnetic dynamics that conspire to induce an IMT. During the course of the photoinduced IMT (above gap excitation), we observe an ultrafast (< 180 fs) quenching of magnetic order followed by a slower collapse of the insulating phase probed by X-ray absorption and THz transmission (∼450 fs). Pump wavelength dependence indicates that an intersite charge transfer (ICT) excitation is a crucial ingredient to initiate the non-thermal IMT dynamics. Density functional theory (DFT) calculations reveal a consistent scenario where ICT drives a collapse of antiferromagnetic order, dynamically preparing NNO for subsequent octahedral breathing mode relaxation that leads to the metallic phase.

**Popular Summary:**

Certain materials can exist as either insulators or metals corresponding, respectively, to the tendency of electrons to localize or roam freely throughout a crystal. Such emergent phases ultimately arise from competition or cooperation between microscopic degrees of freedom (DOF). Subtle changes between the operative DOF - often upon changing the temperature of the sample - can trigger an insulator-to-metal transition (IMT), the understanding of which remains a grand challenge of fundamental importance in condensed matter physics. The microscopic DOF under consideration include electron-electron repulsion, lattice motion, and magnetism associated with the electron spin, all of which can conspire to drive an IMT. To unravel the interactions between these DOF that results in an IMT requires a concerted effort, necessitating state-of-the-art materials and experimental probes in cooperation with advanced theory and computation. Transition metal oxides provide a plethora of IMT materials, and we have chosen to investigate the nickelate NdNiO$_3$ (NNO), where magnetism and the lattice play important roles in driving the IMT. In particular, at low temperatures, NNO exists as an insulator with antiferromagnetic spin ordering, transitioning to a paramagnetic metal above 150 K. We have interrogated NNO using short pulses of x-rays. The x-rays are capable of simultaneously probing magnetic and lattice dynamics, initiated with a short pulse of light that disrupts the low temperature insulating phase. The dynamics, tracked in the time domain, reveal an initial rapid collapse of the magnetic order that, in turn, drives a structural reconfiguration en route to the final metallic state. Theory supports this scenario, indicating subtle cooperativity between the lattice and magnetic order in determining whether an insulating or metallic phase is obtained. We envision that our approach is applicable to numerous other transition metal oxides that exhibit IMTs or other exotic phases such as superconductivity.

**INTRODUCTION**

In quantum materials, long-range order and macroscopic functionality emerge from microscopic interactions between structural, electronic, orbital, and magnetic degrees of freedom. Quite often, these degrees of freedom are deeply intertwined, leading to competing, coexisting, or even cooperative orders [1–3]. It is imperative to experimentally disentangle these subtle interactions to unlock the full potential of the myriad of phenomena embedded in quantum matter. Directed property control using static-tuning knobs such as strain, electrostatic gating, or magnetic fields provides a promising route to explore complex energy landscapes with the possibility of selecting a particular ordered quantum phase [4]. In the context of these materials, a fundamental transition to study is the insulator-to-metal transition (IMT), that is ubiquitous yet often not well understood[5].

The main challenge in understanding the IMT in many systems is the cooperative coupling between the lattice structure, electronic order, and the magnetic configuration that occurs in a wide variety of transition metal oxides (e.g. manganites[6], cobaltites[7], ferrites[8], vanadates[9], nickelates[10]). This arises due to the highly connected nature of the lattice[11–14] that results in an interplay between changes in electronic and
magnetic order with many structural degrees of freedom such as distortions, octahedral rotations and cation displacements. Recently, some data has been assembled and analyzed to explore correlations between structural, electronic, and magnetic order[15–17], which is insightful but not always conclusive. This leads to a challenging problem that is difficult to disentangle especially in the case where multiple order parameters change under the same physical conditions.

By moving beyond equilibrium probes, an alternate approach is to utilize ultrafast stimulation with optical pulses to explore the energy landscape and follow how phases evolve with time during conversion between quantum states. This route can make it possible to disentangle how microscopic competing degrees of freedom lead to the emergence of long range order [18–20], with the ultimate goal of light directed property control [21]. Indeed, ultrafast techniques now span the electromagnetic spectrum enabling multi-modal studies of complexity in solids. Ultrafast X-ray techniques have risen to prominence making it possible to directly and simultaneously probe different degrees of freedom at their fundamental timescales [22–34]. To that end, ultrafast X-ray measurements can monitor the evolution of structural, electronic, and magnetic changes during the course of a photoinduced IMT. Here we will show how to achieve temporal discrimination together with the selectivity of these new X-ray probes to track specific time-scales for each degree of freedom, to gain a deeper understanding of systems with strongly coupled order parameters.

In this article, we illustrate a paradigm using ultrafast soft X-ray scattering and absorption capabilities at the Linac Coherent Light Source (LCLS) to probe the electronic and magnetic degrees of freedom directly in order to disentangle multiple interactions in a correlated oxide. NdNiO$_3$ has combined antiferromagnetic (AFM) and charge order (CO) that collapse simultaneously at the IMT. The magnetic scattering is sensitive to the long-range spin order associated with the AFM-‘E’ wavevector, while XAS is sensitive to the local Ni coordination connected to the breathing mode distortion of the charge ordered (CO) state and changes in screening due to the IMT [35, 36], which is supported by optical pump - THz probe measurements. Thus, following short pulse excitation, it is possible to independently track the magnetic and electronic dynamics on ultrafast timescales. As described in detail below, for above gap excitation, there is a rapid collapse of the magnetic state (<175 fs) followed by a slower relaxation of the breathing mode CO and IMT response (~450 fs). From comparison between experiment and theory, we can develop a clear picture of the pathway where an intersite charge transfer (ICT) that triggers a collapse in the magnetic state followed by a slower IMT triggered by a displacive excitation of a coherent Nd soft phonon mode, which was observed via modulation of the Nd magnetic order (see Fig. 1(a)). We will refer here to the leading distortion modes[15, 17] that are relevant for the monoclinic to orthorhombic (M-O) symmetry change that is always observed at the IMT in the structural refinements at equilibrium in RNiO$_3$ compounds to connect these with our ultrafast dynamics results as well as with theory. We depict

![FIG. 1. Coupled order parameters](image)

the IMT transition pathway starting from ultrafast melting of AFM order, followed by lattice responses, including octahedral rotation changes ($R_t^+$ and $M_3^+$ distortions), and antipolar A-site cations displacements ($X_5^+$) that couple to the breathing mode ($R_t^+$) and ultimately dictate the response time of IMT transition. Our results can accordingly provide a direct visu-
alization of the IMT, which was not accessible under steady state equilibrium interrogation.

EXPERIMENT DESCRIPTION

The perovskite nickelate NdNiO₃ is a prototypical system with coupled order parameters, exhibiting concomitant charge and magnetic order associated with an IMT (Refs. 10, 35, and 37 and references therein). Charge order is associated with an orthorhombic to monoclinic structural transition involving two NiO₆ sites in the monoclinic phase, which are referred to as short-bond (SB) and long-bond (LB) (see Fig. 1A). The magnetic order is E′-type antiferromagnetic (AFM) with a 4×4×4 pseudocubic unit cell (2×1×2 monoclinic unit cell) with large planes of ferromagnetically aligned LB (S = 1) and small SB (S = 0) Ni sites arranged in an ... pattern as shown in Fig. 1B [38–40]. Although the nominal ionic ground-state is Ni³⁺ in a low spin 3d⁷ configuration (A⁷ B⁶ C⁶ D⁶), theory strongly supports a state that is 3d⁸ L where L denotes a ligand hole on the oxygen site. In this scenario, the charge ordered phase corresponds to alternating 3d⁸ LB and 3d⁸ L² SB sites [41–48]. For NdNiO₃, the question arises of how the cooperation between magnetism and charge order drives the IMT? Theory suggests that the magnetic order is the main driver and supports the CO phase [44, 47, 49], but this has been difficult to show directly on the experimental side and motivates our time domain studies.

The (001) oriented films were grown using pulsed laser deposition on NdGaO₃ substrates (tensile strain of 1.4 %) with a thickness of 50 nm [37, 50]. Experiments were performed at the SXR end-station where the X-rays and laser pulses arrive colinearly with the polarization in the scattering plane (see Fig. 2A) [51]. The sample was cooled below the IMT transition temperature (T_{IMT} ≈ 150 K) to 70 K and aligned to measure the off-specular ((1/4, 1/4, 1/4) pseudocubic Bragg peak corresponding to the AFM-E′ order [40, 52]) as well as the bulk sensitive X-ray absorption spectroscopy (XAS) in fluorescence yield (see Fig. 2B), where the vertical line shows the energy chosen for the time-resolved measurements. Since the main change in the XAS across the IMT is seen at the dip near 852.5 eV (see temperature dependent XAS in the supplement Fig. S2), this energy was chosen to measure both channels without changing the photon energy. The pulse duration for this experiment was ~100 fs for the X-ray pulses and ~150 fs for the laser, which gives a total time resolution of ~175 fs. Excitation pulses at 1.55 eV were utilized in addition to mid-IR pulses generated using optical parametric generation and difference frequency generation (~83 - 135 meV) to enable above and below gap pumping (optical gap E_g ≈ 100 meV) [53]. Additionally, the insulator-to-metal transition dynamics of the NdNiO₃ thin film was explored with optical pump-THz probe spectroscopy to track the formation of the metallic phase. To achieve optimal temporal resolution, the experiment was implemented in the following way: (i) both excitation (optical) and probe (THz) beams were collinear and incident on the sample at normal incidence to eliminate temporal broadening of rising dynamics introduced by oblique incidence of excitation beam. The 1.55 eV reflectivity (ΔR/R) dynamics were measured with pulses having a duration of ~20 fs.

RESULTS

Ultrafast spectroscopy and scattering

The ultrafast electronic and magnetic dynamics are presented in Fig. 3A, which shows the pump-probe delay scans from magnetic scattering and XAS measurements following 1.55 eV excitation. At an excitation level of ~0.01 electrons per nickel site (0.5 mJ/cm²), the magnetic scattering is completely quenched within 175 fs. In dramatic contrast, the time-resolved XAS scan shows a longer transition time of 446 fs, which demonstrates that the magnetic and electronic contributions to the IMT have different timescales. For all of the data, the transition times were determined by fitting to an error function together with a slower exponential recovery. Note that the quoted transition times are defined by the twice the Gaussian width (width defined by difference at 0.85 and 0.15 of maximum value) and fitting errors were all < 10 fs. Clearly, the magnetic order collapse is at the limit of our temporal resolution while the XAS dynamics are substantially longer. This indicates a rapid and total collapse of the magnetic order prior to changes in the CO (breathing distortion) and IMT embodied...
FIG. 3. **Magnetic and electronic dynamics** (A) Delay scans for the magnetic scattering and XAS data following 800 nm excitation. The scale for the magnetic scattering is 1 for static AFM order and zero for complete loss of long-range order. XAS is a relative change consistent with the magnitude of XAS change seen with crossing IMT (see Fig. S2). (B) THz transmission overlayed with XAS. (C) Nd magnetic scattering intensity at the same wave-vector as Ni. The thin vertical line is at time-zero while the second line is after 1 period of the coherent phonon.

in the XAS response. To track the IMT directly, we utilized optical-pump THz-probe measurements to directly follow the formation of the metallic state. As shown in Fig. 3B, the THz response shows a transition to the metallic phase that correlates directly with the XAS signal. The transition time to the metallic phase from the THz transmission is 425 ± 15 fsec, consistent with the XAS timescale. From this we can confirm that the ultrafast IMT is occurring at a slower timescale than the collapse of the long-range magnetic order.

In addition, we performed ultrafast degenerate 800 nm pump-probe measurements of the optical response with 20 fs time resolution. The comparison of the magnetic scattering response with the ΔR/R (see Figs. S3 and S4) shows that the ΔR/R response (transition time 228 ± 3 fs), is somewhat slower than the time-resolution-limited magnetic response. However, both our calculations (supplemental Fig. S8) and Ref. 54 demonstrate that the near infrared reflectivity dynamics (800 nm R/R) are influenced by changes in both electronic and magnetic order. The transition in the optical data does not show any evidence for two separate timescales so without a comprehensive model of how the optical spectra evolve with time, it is hard to extract numbers beyond observing that the data supports more than one timescale in the system. In the supplement (see Fig. S5), we present the data for pump wavelength dependence suggesting that the fast time-scale is associated with above-gap excitation and does not depend on the energy in excess of the NdNiO₃ bandgap. Nevertheless, we argue that the magnetic sensitivity contribution of the optical reflectivity captures in turn a somewhat faster transition time than what we observe in the purely electronic channels, including XAS and THz signals.

We also tracked the induced order on the Nd site as an additional probe of the changes in the magnetic order where the long-range Nd order arises from a very weak magnetic coupling to Ni via the Nd-O-Ni bonding. By tuning to the Nd M₄ resonance (~1000 eV) at the same wave-vector as the Ni ordering[52], we explored how the Nd ordering responds to the change in Ni ordering. In addition to a fast initial drop at the same rate as the collapse of Ni magnetic order (see Fig. 3C), there is a strong oscillatory component with a period of ~450 fs that is rapidly damped within a few ps, due to a coherent phonon rather than a Nd magnon. The oscillation period is consistent with the soft phonon associated with the Nd site[55], which we also observed with optical reflectivity (Figure S6). The ringing in the Nd magnetic scattering is related to changes in the Nd-O-Ni exchange path and the time-scale of the damped oscillation is consistent with time-resolved measurements of the collapse of the CO state[56]. Note that the fit to Nd data was restricted to the early time region (between Nd intensity of 0.6 and 1) and results in the same width of initial drop in order as the Ni case, which implies the Nd senses the Ni long-range order collapses in the first 200 fs. This connection and the coherent phonon mode will be explored in more detail in the discussion section.

**Theory**

To obtain additional insight into how magnetic order couples to the lattice, we used density functional theory (DFT) to examine the electronic structure and energetics of various magnetic states as a function of static lattice distortions. The energetics of the AFM-E’ monoclinic structure is compared against the ferromagnetic (FM) solution, which in this context serves as a proxy of the paramagnetic (PM) state, which is difficult to approximate at the DFT level. However, note that the FM solution that is provided solely by DFT has orthorhombic symmetry and thus captures well the essential structural characteristic of the structural M-O transition observed during IMT. To include the influence of correlations, a plus Hubbard $U = 2$ eV correction was used on the Ni d orbitals, which accurately captures the details of the AFM insulating phase [47]. Specifically, we investigate the evolution of the magnetic order parameter in the Nd site and its role in the transition to the metallic state.
and electronic properties as a function of the breathing mode distortion (Fig. 4A). We focus on this particular distortion as it is the primary distortion active at the P\textit{r}\textit{3}m\textit{a} \rightarrow P\textit{2}1/\textit{n} transition; in addition, the DFT studies indicate that Jahn-Teller and rumpling distortions are not operative in determining the magnetic order (see Figure S4).

As a function of the cooperative breathing mode distortion, Fig. 4A plots two energy curves corresponding to insulating AFM-E' and ferromagnetic (FM) order[17]. The minimum for the AFM case agrees with the experimental value of the breathing mode distortion and the resulting magnetic order has \( S \sim 1 \) on the LB site and \( S = 0 \) on the SB site. The AFM phase is insulating at all magnitudes of breathing distortion, but the FM phase is only insulating at values of breathing distortion greater than point C (additionally, see Figs. S7 and S9). Although a non-collinear spin structure also satisfies the symmetry for E'-type order [38–40, 52], our results together with other recent theoretical results strongly suggest that the collinear phase is the stable ground magnetic state [47, 48]. The energy of the FM state is always higher than the AFM state except close to zero breathing mode distortion, corresponding to the high temperature orthorhombic symmetry of the paramagnetic metallic phase. Further, we note that the gap between AFM and FM at the AFM minimum is \( \sim kT_N \). To understand the evolution of these different degrees of freedom upon optical excitation, we consider a two step process. Step 1 (see Fig. 4A), corresponds to direct excitation from points A to B at a timescale faster than the lattice can respond and alter the cooperative breathing mode distortion (i.e., a shift along the horizontal axis). As shown by the density of states (DOS) in Fig. 4B, at this point on the FM curve, the system is still insulating. Since point B is not at the minimum of the FM energy curve, the system will then move towards smaller breathing distortion and the minimum located at point C, where the system becomes metallic (see insets of Fig. 4B).

**DISCUSSION**

Now we can link these results in order to understand the fundamental question of what controls the time-scales for phase transformation in a strongly coupled phase with multiple order parameters. This insight can allow us to build a more complete picture of how light interacts with these degrees of freedom. First, we discuss the nature of the optical excitation process. In the case of highly-covalent nickelates, our calculations of the optical spectra (see supplement) and those with DMFT theory in Ref. [54] are consistent with an intersite charge transfer (ICT) from the 3d\(^8\) LB sites to 3d\(^8\) S\(^2\) B sites involving excitations between the Ni 3d and O 2p states. This ICT dynamically changes the charge distribution around the lattice sites. From our analysis of the calculated density of states above, two key components change between AFM (A) and FM (B) configurations. First, the local moment on the SB site, which is 0\(\mu_B\) for the AFM phase converts to \( \sim 0.5\mu_B \) in the FM state. This arises from a local rearrangement of the spin-dependent \( e_g \) orbital occupancy on the SB site. Secondly, the difference in Born effective charges between the LB and SB sites increases (see details in supplement Table S3). This is associated with the redistribution of oxygen holes in the lattice due to the change in magnetic state, similar to the process that would be triggered via light induced ICT. Such an excitation has pathways for directly coupling to magnon excitation and allows the light to couple to the magnetic degree of freedom[57].

Understanding the excitation pathway allows one to address the question of what controls the fundamental timescales for collapse of these different degrees of freedom. For other complex oxide systems, the timescales for the charge transfer excitation and rearrangement of orbital occupancies has been shown to occur on sub-\( \sim 100 \text{ fs} \) timescales [29, 58, 59]. As such, we consider ICT an operative pathway by which changes in the electronic configuration modify the magnetic order via optical modification of the exchange and the time-scale for the collapse of magnetism is then tied to the details of the spin-wave spectrum[60]. This is due to the momentum conserving optical excitation of bimagnons as observed in other transition metal oxides[57]. Indeed, recent resonant inelastic X-ray scattering measurements measured the magnons in NdNiO\(_3\) for the first time and show that the zone-boundary magnons in NdNiO\(_3\) have \( \sim 50 \text{ meV energy}\)\((\sim 85 \text{ fs period})[61] \), which is consistent with our inference of a sub-100 fs timescale that leads to the vertical transition from points A to B in Fig. 4A.
Since the AFM order supports the charge order for \( \text{NdNiO}_3 \), the collapse of magnetic order triggers a collapse of the CO phase. Nevertheless, since our experiments demonstrate a slowed response for CO with respect to the melting of the magnetic order, we discuss the origin of this observation in the following.

From bulk \( \text{NdNiO}_3 \) it is known that the paramagnetic phase can exist in the presence of CO so a change in lattice symmetry is not required for the collapse of magnetic order. However, the metallic state is only present in orthorhombic symmetry. On the structural side, the collapse of the CO is key to the transition to the higher symmetry metallic phase, but the breathing mode is coupled to a low energy Nd mode that is directly associated with the \( P2_1/n \rightarrow Pnma \) structural phase transition[15]. In support of this point, we find a linear relationship between the \( X^+_{5} \) distortion that is characteristic for A-site cation distortion and the breathing mode \( (R^+_{4}) \) distortion as observed from equilibrium state refinements[15, 17] (see Fig. S10). Since \( X^+_{5} \) is also coupled to the \( R^+_{4} \) and \( M^+_{3} \) octahedral rotation distortions involved in M-O symmetry change at IMT, we expect that a collective structural response is needed under a dynamical structural transformation. Owing to the coupling of these two modes, the timescale will be dictated by the slowest mode (i.e. phonon bottleneck) and is consistent with the timescale seen for the electronic changes, as was seen recently for the case of layered nickelates [62] and was already known for \( \text{VO}_2[63] \). This expected time-scale is also consistent with recent ultrafast measurements of the collapse of the CO state[56] and connects to the clear coherent phonon oscillation seen via the Nd magnetic scattering (see Fig. 3C).

To better understand this coherent phonon mode and how it connects to the induced Nd magnetic order[52, 64], we utilized theoretical calculations (see supplement) and insight from calculations of Nd-TM coupling for the case of \( \text{NdFeO}_3[65] \) as no such calculations exist for \( \text{NdNiO}_3 \). Figure 5A, shows a portion of the unit cell with the Nd atom and the shortest exchange pathway to the high-moment Ni\(_{LB}\) site. Calculations show that this \( \sim 80 \text{ cm}^{-1} \ \text{A}_g \) symmetry mode involves motion of the Nd atom that drives a tilting/rotation of the NiO\(_6\) octahedra without any motion of the Ni atom. Since the exchange, \( J_{\text{Nd-Ni}} \), is directly connected with the Nd-O bond length, this provides a direct connection between the magnetic exchange and the lattice vibrations. If the bond length changes, \( J_{\text{Nd-Ni}} \) varies and the induced Nd order varies correspondingly. To look at this mode in more detail, we show two fluences for the measurement of the Nd induced order. Both show a clear coherent mode and the fact that it has a longer lifetime at low fluence associates this with an excitation in the insulating phase (see Fig. 5B). To quantify this mode more directly, we will break the Nd data into two parts: a fast initial decay followed by a slow recovery and the coherent oscillation.

In the first 200 fs, the Nd magnetic collapse has the same timescale as the Ni magnetic data implying a connection between the two processes. Usually the parasitic Nd order is considered as a paramagnetic moment in the large local field due to proximity to the ordered Ni atoms, as was evidenced in resonant soft X-ray scattering at the Nd M-edge[52]. To first order, one would accordingly expect a slow paramagnetic relaxation and not an ultrafast response. However, recent work has shown that in \( \text{ErFeO}_3 \) the Fe magnons hybridize partially with Er spin fluctuations[66], providing a partial pathway for the Ni magnetic excitations to couple to the Nd. This seems...
consistent with the observation that the fast drop in Nd order is roughly proportional to what is seen for the case of Ni. However the the connection to Ni does not explain the coherent oscillation, which was not seen for Ni and has a longer period than expected for Ni magnons (~85 fs period). To quantify the oscillation, we take the difference between the data and a simple fit shown in Fig. 5B and fit a cosine to this difference, we determined the oscillation periods for both fluences to be 378 ± 10 fs. This period is very consistent with the observed phonon modes and our calculations (see supplement) associated with motion of the Nd atom. This phonon causes a coordinated increase/decrease of the shortest Nd-O-Ni bonds highlighted in figure Fig. 5A. Since the magnetic exchange is strongly affected by the change in bond-length, this results in a modulation of the Nd order that has the period associated with the Nd-O phonon.

It is well known that the equilibrium atomic positions for all atoms in the unit cell are strongly affected by the IMT, as is shown in Fig. 4A. An abrupt change in the equilibrium atomic positions arising at the first order transition provides a mechanism for the displacive excitation of phonons. Deeper insight will require developing a model linking the bond-length changes to the magnetic coupling between Nd and Ni. However, the displacive mechanism suggests that as soon as the magnetism is quenched, the lattice knows it must move to a new set of equilibrium positions. This together with the different timescales for magnetism and the IMT are consistent with a picture that for NdNiO$_3$, the antiferromagnetic order is the primary order that supports the CO phase. Such a conclusion has been suggested theoretically, but has been too difficult to prove experimentally given the concomitant nature of the electronic and magnetic phase transitions. Here using time-domain techniques we were able to extract more insight from the fundamental timescales and show clearly that magnetism is the driver of the IMT by showing the initial magnetic collapse is what triggers the loss of CO and subsequent IMT.

Now we can expand the context and discuss this in connection to a much wider class of materials with entangled order parameters. It is useful to consider the present results in the context of other ultrafast experiments on NdNiO$_3$ and more generally in the context of photoinduced IMT dynamics in other materials. In comparison to vanadates such as VO$_2$ and V$_2$O$_3$, the IMT in NdNiO$_3$ has a fluence threshold that is nearly an order of magnitude smaller. This is, in part, related to the large (relative) latent heat in the vanadates, necessitating a larger absorbed energy density to obtain the high temperature metallic structure. V$_2$O$_3$ is similar to NdNiO$_3$, with a high temperature paramagnetic metallic state that transitions to a low temperature antiferromagnetic insulating phase ($T_{\text{IMT}} \approx 150 K$). Despite these similarities, the dynamics of the photoinduced IMT in V$_2$O$_3$ is more similar to VO$_2$. Specifically, there is no evidence of magnetism playing an important role in triggering the IMT in V$_2$O$_3$. This further highlights the unique cooperativity of magnetism and the lattice in triggering the IMT in NdNiO$_3$ following photoexcitation.

**CONCLUSION**

In summary, using X-rays to disentangle the electronic and magnetic degrees of freedom has provided a concise picture of how light interacts with strongly correlated matter. By tracking the distinct timescales one can gain not only a clearer picture of how charge, magnetic, orbital, and lattice orders evolve, but also which are key to driving the transition and which are triggered as a response to the changing fundamental order parameter. Using this approach, not only can we see that magnetic order is likely the fundamental order parameter for NdNiO$_3$, but also provides a paradigm to unravel entangled order parameters in many of the complex materials of contemporary interest.

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