

# Possible common ground for the metal-insulator phase transition in the rare-earth nickelates $R\text{NiO}_3$ ( $R = \text{Eu, Ho, Y}$ )

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We report on the infrared spectra of  $R\text{NiO}_3$  ( $R = \text{Eu, Ho, Y}$ ). They provide evidence of phonon and insulating gap behavior and point to the monoclinic distortion at the metal-insulator (MI) transition as a feature for all  $R\text{NiO}_3$  ( $R \neq \text{La}$ ). We hypothesize that the intermediate paramagnetic phase (above  $T_N$  and below  $T_{\text{MI}}$ ) in  $R\text{NiO}_3$  ( $R = \text{Sm, Eu, Ho, Y}$ ) might be consequence of a self-doping effect, gradually triggering a phase segregation in electron-rich and electron-poor regions. This picture is concomitant to the temperature-dependent effect of octahedral tilting and distortion and self-trapped electrons in a polaronic medium.

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Rare-earth nickelate  $R\text{NiO}_3$  perovskites have triggered a great deal of interest among solid-state chemists and physicists due to the still not well understood phenomena related to their anomalous magnetic ordering and the metal-insulator (MI) transitions they experience as a function of temperature and the rare-earth size.  $R\text{NiO}_3$  ( $R \neq \text{La}$ ) have been described as orthorhombically distorted perovskites (space group  $Pbnm$ ), the structure of which was unchanged in all the temperature regime; nevertheless, recent high-resolution neutron and synchrotron x-ray studies demonstrated the presence of a low-symmetry-low-temperature phase characterized by a charge disproportionation effect describable in the monoclinic  $P2_1/n$  space group below  $T_{\text{MI}}$ .<sup>1</sup> This change of symmetry concomitant with  $T_{\text{MI}}$  was only observed for the smaller rare-earth members of the  $R\text{NiO}_3$  family,  $R = \text{Y, Ho, ..., Lu}$  (Ref. 1), and only very recently in  $\text{NdNiO}_3$  thin films.<sup>2</sup>

All the  $R\text{NiO}_3$  ( $R \neq \text{La}$ ) perovskites experience an antiferromagnetic ordering below  $T_N$ , which coincides with  $T_{\text{MI}}$  for the larger members of the series ( $R = \text{Pr, Nd}$ ).<sup>3</sup>

It has been puzzling for a long time the reason why the onset of a low-temperature antiferromagnetic ordering at  $T_N$  for the smaller rare-earth nickelates ( $R = \text{Sm, ..., Lu, Y}$ ) seems to have no correlation with the change in conductivity at the temperature  $T_{\text{MI}}$ , in which the metal-insulator phase transition takes place. These oxides experience a sequence of two phase transitions from a (high- $T$ ) paramagnetic conducting to a (low- $T$ ) insulating antiferromagnetic regime in

which  $T_{\text{MI}}$  and  $T_N$  are  $\sim 200$  K apart by an intermediate paramagnetic insulating state. Below  $T_{\text{MI}}$ , a charge-transfer gap is open as an excitation gap from O  $2p$  to the Ni  $3d$  states. Depending on the  $R$  ionic size in  $R\text{NiO}_3$  ( $R \neq \text{La}$ ) governing the charge-transfer integral between O  $2p$  and Ni  $3d$  orbitals, the crossover between metallic and semiconducting behavior in the context of the Zaanen-Sawatzky-Allen scheme is reached at temperatures between 350 K ( $R = \text{Sm}$ ) and 600 K ( $R = \text{Lu}$ ).<sup>4</sup>

Electron-phonon interactions are explicit at frequencies close to longitudinal-optical modes, and in addition, infrared reflectivity put in evidence small polaron hopping conductivity yielding the typical tail of metal oxides.<sup>5</sup> Strong electron-lattice interaction was further verified by the unusually large isotopic shifts of the metal-insulator transition [ $T_{\text{MI}}(^{18}\text{O}) - T_{\text{MI}}(^{16}\text{O}) \sim 10$  K] found by Medarde *et al.*<sup>6</sup> Neutron-diffraction measurements show that there is a linear relation between the metal-insulator transition and the tilting angle of the  $\text{NiO}_6$  octahedra.<sup>6,7</sup>

Here we report on the temperature-dependent infrared activity of  $R\text{NiO}_3$  ( $R = \text{Eu, Ho, Y}$ ) with  $T_{\text{MI}}$  at  $\sim 483$ ,  $\sim 573$ , and  $\sim 582$  K and  $T_N$  at  $\sim 205$ ,  $\sim 145$ , and  $\sim 138$  K, respectively.<sup>8</sup>

Infrared transmission and reflectivity measurements have been done using facilities and techniques already reported.<sup>5</sup> To assure stabilization of  $\text{Ni}^{3+}$  cations in smaller rare-earth nickelates,  $R\text{NiO}_3$  ( $R = \text{Pr, Nd, Sm, Eu}$ ) were prepared at

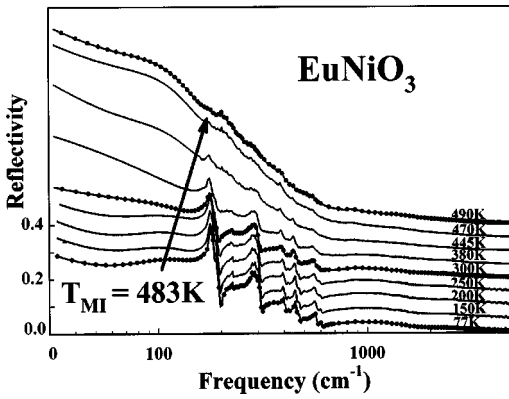


FIG. 1. Infrared reflectivity of  $\text{EuNiO}_3$ . A full line represents experimental measurements and the dots represent reflectivity obtained by dielectric simulation. The spectra have been vertically displaced for better viewing.

1000 °C under high pressure up to 200 bars.<sup>9</sup>  $\text{HoNiO}_3$  and  $\text{YNiO}_3$ , requiring a more oxidizing synthesis, were prepared in a piston-cylinder press. These procedures yielded black, well-crystallized powders, and in the case of  $\text{EuNiO}_3$ , pellets suitable for reflectivity. We stress that throughout these measurements we used fresh samples to avoid  $\text{Ni}^{2+}$  reduction due to superficial hydroxidation or carbonation.

Phonon frequencies and optical conductivity as well as the overall temperature-dependent reflectivity of  $\text{EuNiO}_3$ , Fig. 1, mirror those for  $\text{SmNiO}_3$  where lower symmetry was detected in the insulating phase.<sup>5</sup> Close to  $T_{\text{MI}}$  the electron-phonon interaction becomes evident as antiresonances due to self-trapped electrons near longitudinal-optical frequencies in polarizable oxygen bonds. At about 300 K the number of phonon bands, shown for transmission in Fig. 2(a), signal that a lower than orthorhombic lattice distortion has taken place. Infrared small polaron conductivity, as for other reported nickelates,<sup>5</sup> yields at low temperatures high  $\eta$  values, a parameter characterizing the strength of the electron-phonon interaction, while approaching  $T_{\text{MI}} \sim 483$  K smaller  $\eta$  values are obtained.

Since the  $\text{Ni}^{3+}$  stabilization in  $\text{HoNiO}_3$  and  $\text{YNiO}_3$  requires the internal oxygen pressure generated *in situ* by the decomposition of  $\text{KClO}_4$  (giving  $\text{KCl} + 2\text{O}_2$ ) (Ref. 8), as-grown pellets prepared for reflectivity measurements were contaminated by  $\text{KCl}$  as an undesired impurity, and thus, unsuitable for quantitative reflection measurements. Nevertheless, once the as-grown pellets were ground and the resulting powder was washed in aqueous  $\text{HNO}_3$  (to dissolve  $\text{KCl}$  and eliminate unreacted  $\text{NiO}$  and  $\text{R}_2\text{O}_3$ ), the polycrystalline nickelates were stable and, as Figs. 2(b) and 2(c) show, standard transmission procedures yielded excellent spectra. Phonon bands in the absorption mode, Fig. 2, have the overall temperature dependence reported elsewhere for other nickelates.<sup>5</sup> And again, the signature of the monoclinic distortion is observed below  $T_{\text{MI}}$ . We also note that infrared-absorption spectra are proportional by a frequency-dependent factor to the infrared conductivity.<sup>10</sup> The emerging gap similar to other perovskite oxides,<sup>11</sup> here with a somewhat better defined  $e_g \rightarrow t_{2g}$  band centered at  $\sim 4000$   $\text{cm}^{-1}$  for

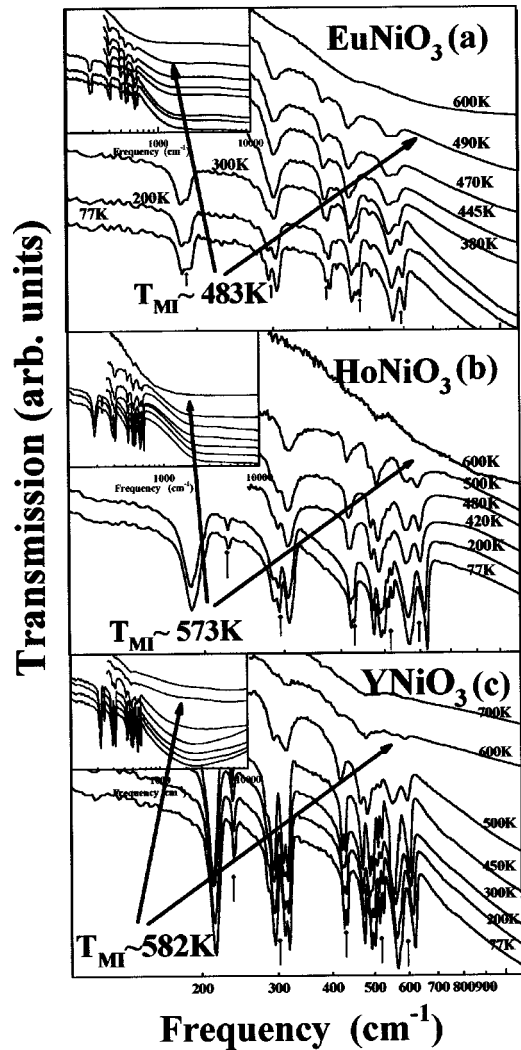


FIG. 2. (a) Infrared transmission phonon spectra of  $\text{EuNiO}_3$  between 77 and 600 K; (b) *ibidem*  $\text{HoNiO}_3$ ; (c) *ibidem*  $\text{YNiO}_3$  between 77 and 700 K. The insets show the overall behavior between 40 and 10000  $\text{cm}^{-1}$ . Arrows signal bands modified by the monoclinic distortion. The higher temperature far-infrared transmission measurements were limited up to 400 K because pellets used in that spectral region are made of polyethylene. The spectra have been vertically displaced for better viewing.

$\text{YNiO}_3$ , Fig. 2(c), does not have traces near its edge ( $\sim 94$  meV =  $752$   $\text{cm}^{-1}$  at 77 K, 0.25-meV resolution) of subtle substructures close to  $T_N$  that might be associated with an onset of antiferromagnetic ordering.

The consequence of a monoclinically distorted  $P2_1/n$  lattice in  $\text{EuNiO}_3$ ,  $\text{YNiO}_3$ , and  $\text{HoNiO}_3$  is the existence of two crystallographically independent nickel sites and three kinds of nonequivalent oxygen atoms where each  $\text{NiO}_6$  octahedra is linked to six  $\text{Ni}_2\text{O}_6$  octahedra. We have already reported that the amplitudes of Fourier transform of extended x-ray absorption fine structure (EXAFS) oscillations, i.e., the pseudoradial distribution functions, reveal that this finding may be extended to the large rare-earth members  $\text{RNiO}_3$  ( $R = \text{Pr}, \text{Nd}$ ) as a small departure from the orthorhombic symmetry. This implies either a distortion in the  $\text{NiO}_6$  octahedra

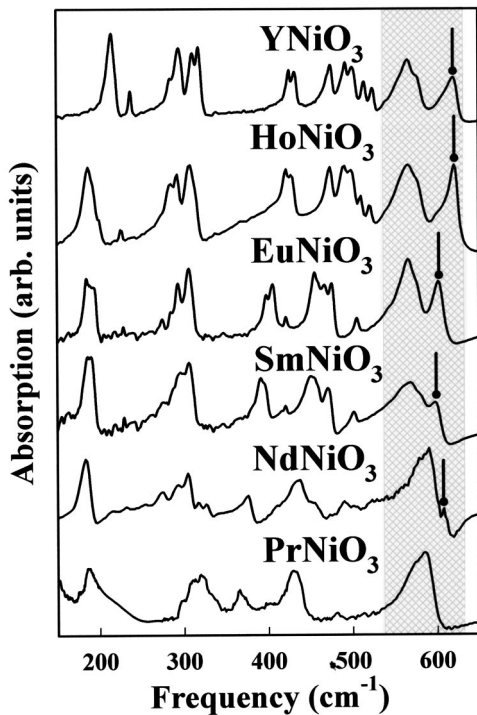


FIG. 3. Lattice absorption spectra of  $RNiO_3$  ( $R \neq La$ ) at 77 K.

(identifiable with a Ni Jahn-Teller distortion) or that there are two different Ni sites in the insulating phase.<sup>12</sup> This, in turn, distinctively points to a structurally lower symmetry near and below  $T_{MI}$  that correlates well with charge disproportion as a more subtle monoclinic distortion for the larger rare-earth perovskites. The reported orthorhombic space group for  $EuNiO_3$  above, but near,  $T_{MI}$  would be consequence of averaging in the neutron-diffraction analysis.<sup>12</sup>

In Fig. 3 nickelate phonon bands at 77 K are shown as a function of the rare earth sequencing the degree of structural distortion. Octahedral breathing modes at  $\sim 600$   $cm^{-1}$  are the vibrations that are being more affected by octahedral tilting and shape, i.e., the  $O_{2p}-Ni_{3d}$  hybridization, and have bands where the overall multiplicity is better depicted. Note that the least distortion, in accordance with Piamonteze *et al.*,<sup>12</sup> is for  $PrNiO_3$ , where there is only a main band asymmetry and not an explicit phonon splitting. We do not observe a two-group separation as in susceptibility measurements.

We then suggest that all  $RNiO_3$  ( $R \neq La$ ) share a common triggering mechanism of the metal-insulator phase transition related to octahedral tilting and distortion and to self-trapped electrons in a polaronic medium. Similarly, we infer that spin ordering *per se* is not a good order parameter in simple nickelates. This conclusion is strongly supported by recent independent measurements by electron diffraction and Raman scattering. It is reported that the metal-insulator phase transition in  $NdNiO_3$  thin films is associated with important structural and vibrational changes at  $T_{MI}$  described by a  $Pbnm$  to  $P2_1/n$  lattice phase transition.<sup>13</sup> And, as it was pointed out above, charge order in  $NdNiO_3$  films had been observed at the metal-insulator transition using resonant x-ray scattering implying a long-range ordered ground state with two distinct Ni sites,  $Ni^{3+\delta}$  and  $Ni^{3-\delta'}$ , with  $\delta + \delta' = 0.42 \pm 0.04e$  (Ref. 2).

The driving force for the monoclinic distortion leading to two independent positions for Ni is also ordering between two differently charged Ni cations for the last six members of the  $RNiO_3$  series.<sup>1,11</sup> In these last ones the insulating phase consists of expanded ( $Ni1O_6$ ) and contracted ( $Ni2O_6$ ) octahedra that alternate along the three directions of the crystal, with evidence of an incomplete stabilization of a charge disproportionation,  $2Ni^{3\pm\delta} \rightarrow Ni^{3+\delta} + Ni^{3-\delta}$ , a mutual self-doping process, with mean value of  $2\delta = 0.6$  electrons;<sup>1</sup> i.e., an incomplete  $2Ni^{3+} \rightarrow Ni^{2+} (S=1) + Ni^{4+} (S=0)$  process.

Thus, a more compatible picture may be proposed for all  $RNiO_3$ . We conjecture that the unusual spin propagation vector  $\mathbf{k} = (1/2, 0, 1/2)$  (Refs. 1 and 14) in a net antiferromagnetic arrangement, the results of alternating nearest-neighbors  $Ni^{3+}$  ions in ferromagnetic and antiferromagnetic couplings, and the temperature divorce in  $T_N$  and  $T_{MI}$  may be a consequence of the triggering of a self-electron-doping effect, leading to the separation between electron-rich and electron-poorer regions. These anomalies near  $T_{MI}$  will usher local monoclinic-like lattice malformations with an overall single structural environment. It is known that in oxides, as in  $CaMnO_3$ , hole doping induces a magnetic transition without a significant variation in the lattice constants,<sup>15</sup> and on going from  $LaMnO_3$  to  $TbMnO_3$ , close to the limit for a distorted perovskite structure, the complexity of the magnetic structure increases as the rare-earth reduces in size.<sup>16</sup> Further, since the onset of antiferromagnetic order in smaller rare-earth nickelates is not sharp, segregation, difficult to detect with x-ray or neutron-diffraction techniques, may play a role in the insulating paramagnetic phase. Paraphrasing findings currently discussed for manganese compounds in the context of electronic mixed phases,<sup>17</sup> different charge densities, and magnetic states are expected to coexist and, in our case, would only consolidate the magnetic order at  $T_N$  due to temperature-dependent electron localization that may include Jahn-Teller effects. In  $Tb_{0.01}Ca_{0.99}MnO_3$  (Ref. 15), whose resistivity (similar to  $NdNiO_3$ ) has a rather sharp metal-insulator phase transition, spontaneous charge separation induces magnetic separation corresponding to electron-rich and electron-poor microregions.<sup>16,18</sup> In  $RNiO_3$ , inhomogeneous regions with charge separation ( $2\delta$ ) and associated net spins close to  $S=1$  ( $Ni^{2+}$ ) and  $S=0$  ( $Ni^{4+}$ ) may only consolidate at  $\sim T_N$ . Localization, directly observed in infrared reflectivity close to the longitudinal-mode frequencies (e.g., Fig. 1), is a gradual effect heavily dependent on the temperature. Then, space inhomogeneities, influencing spin order, may be thought as the common feature with a more subtle degree of charge separation for the case of larger rare-earth cations. This, in turn, suggests that charge density is the order parameter of the metal-insulator phase transition. As pointed by Vobornik *et al.*<sup>19</sup> for those nickelates in which  $T_{MI} \sim T_N$ , most of the experimental findings state that  $T_{MI}$  is independent of magnetic interactions and we feel that a theoretical approach along mixed phase separation concept may help in bringing together the apparent unlike behavior in the  $RNiO_3$  ( $R \neq La$ ) family. It also calls for increasing experimental resolution of neutron, x-ray (i.e., techniques dealing with long-range ordering) photoemission measurements to clear the understanding of the overall picture of these fascinating compounds.

*Note added.* We recently became aware of a publication by Yamamoto and Fujiwara [J. Phys. Chem. Solids **63**, 1347 (2002)] with calculations relying in older measurements that assign two different crystallographic space groups for NdNiO<sub>3</sub> and YNiO<sub>3</sub>, respectively. We believe that under the light of Refs. 2, 12, and 13, as well as the results reported here, their basic hypothesis ought to be revised. We also note that the same observation applies in analyzing the results of

substituting Ni by Fe in a more recent publication by Kim *et al.* [Phys. Rev. B **66**, 014427 (2002)].

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