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# Role of the rare earth in lattice and magnetic coupling in multiferroic $h$ – $\text{HoMnO}_3$

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We used Raman scattering to study the lattice and magnetic excitations in the hexagonal  $\text{HoMnO}_3$  single crystals. The  $E_2$  phonon mode at  $237\text{ cm}^{-1}$  is affected by the magnetic order. This mode is related to the displacement of Mn and O ions in the  $a$ - $b$  plane and modulates the Mn-O-Mn bond angles in the  $a$ - $b$  plane and in the in-plane Mn-Mn superexchange interaction. The mode at  $269\text{ cm}^{-1}$  associated to the displacement of the apical  $\text{Ho}^{3+}$  ions along the  $c$  direction presents an abrupt change of slope at  $T_N$ , showing that the role of the rare-earth ions cannot be neglected in the magnetic transition. We have identified magnon and crystal-field excitations. The temperature dependence of the magnetic excitations has been compared to the Mn and Ho moment and indicates that the exchange-interaction pattern between Mn and Ho atoms drives the uniaxial anisotropy gap above the Mn-spin-rotation transition.

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## I. INTRODUCTION

Multiferroics [1], which exhibit coexistence of magnetism and ferroelectricity with cross coupling, are of great scientific and technological interest for further spintronics, magnonics, and nanoelectronic devices. These include new forms of magnetoelectric memories, electrically controlled magnonic elements, or domain-wall-based devices with engineered magnetic structure [2–6]. Additionally, these compounds can combine multiferroic orders and geometrical frustrations at low dimensionality that provide unusual spin dynamics as well as phase transitions [7].

Rare-earth manganites ( $\text{RMnO}_3$ ) are one of the canonical examples of multiferroics and are one of the most investigated families. These compounds crystallize in two different structures as a function of the ionic radius: orthorhombic structures for larger ionic radius ( $R = \text{La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy}$ ) and hexagonal structure (space group  $P6_3cm$ ) for  $R$  with smaller ionic radius ( $R = \text{Ho, Er, Tm, Yb, Lu, Y}$ ) [8–10]. Both exhibit multiferroicity, but the microscopic origins are different. The magnetic frustrations in the orthorhombic manganites lead to spin-lattice coupling induced by the inverse Dzyaloshinski-Moriya interaction [9]. The ferroelectricity in the hexagonal compounds results from electrostatic and size effects that lead to the bulking of  $\text{MnO}_5$  bipyramids and the displacement of the rare-earth ions [11].

For each rare-earth manganite, the interactions between the lattice and magnetic degrees of freedom need to be clarified. Hexagonal  $\text{HoMnO}_3$  is one of the most studied of the rare-earth manganites and has a magnetic field-temperature phase diagram that exhibits a multitude of complex spin structures [12–14]. Recently, the antiferromagnetic spin dynamics in  $\text{HoMnO}_3$  has been studied, tracking the changes in the magnon modes with THz pulses [15]. The development of the time-resolved experiments to probe the phonon and spin dynamics show the importance of first understanding the static interactions. Moreover, the stability of a magnetic configuration rather than another and the nature of the spin waves have to be understood. The magnetic properties of  $h$ - $\text{HoMnO}_3$  rare-earth manganite have been studied by inelastic neutron scattering [16], second harmonic generation [13,14], and

low-heat transport [17], whereas the lattice vibrations have been investigated by Raman and infrared [18] spectroscopy. However, the studies of the static coupling between the lattice and magnetic degrees of freedom on  $\text{HoMnO}_3$  single crystals remain small in number [19,20].

Here, we have investigated the  $A_1$  and  $E_2$  phonon modes of  $h$ - $\text{HoMnO}_3$  with polarized Raman spectroscopy. The temperature dependence of particular phonon modes associated to motions modulating the super-superexchange paths between adjacent Mn planes and modulating the Mn-O-Ho interactions shows that the Mn-Mn and Ho-Mn interaction along the  $c$  axis plays an important role in the magnetic ordering in  $h$ - $\text{HoMnO}_3$ . The magnetic excitations have also been measured and spin excitations have been identified. The temperature behavior of the magnon modes shows that the interaction between the rare earth and the Mn atoms controls the uniaxial anisotropy gap from  $T_N$  down to the Mn-spin-rotation transition.

## II. EXPERIMENTAL DETAILS

$\text{HoMnO}_3$  single crystals were grown using the high-temperature flux growth technique in a platinum crucible [21]. The crystals are millimeter-size platelets with a thickness around 0.1 mm and a large surface of  $0.5\text{ cm}^2$ . The hexagonal  $c$  axis is perpendicular to the surface. The crystals have been polished to obtain high surface quality for optical measurements. Raman scattering is performed in backscattering geometry using the 532 nm excitation line from a laser diode and collected by a triple spectrometer Jobin Yvon T64000 equipped with a liquid-nitrogen-cooled charged-coupled device (CCD). The high rejection rate of the spectrometer allows one to detect the low-frequency excitations. Measurements between 10 and 300 K have been performed using an ARS closed-cycle He cryostat.

## III. RESULTS AND DISCUSSION

$\text{HoMnO}_3$  crystallizes in a hexagonal lattice, space group  $P6_3cm$ . This compound is formed by layers of corner-sharing trigonal  $\text{MnO}_5$  bipyramids arranged in a layered-type structure

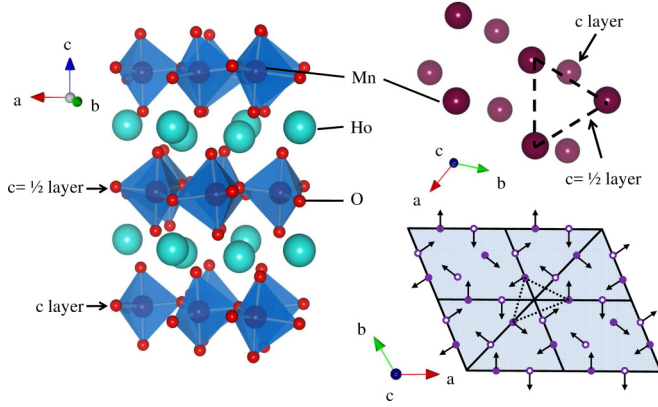


FIG. 1. Crystallographic structure of hexagonal  $\text{HoMnO}_3$  ( $P6_3cm$  phase) and the magnetic order.

in the  $a$ - $b$  plane with apical ( $\text{O}_1$ ,  $\text{O}_2$ ) and in-plane ( $\text{O}_3$ ,  $\text{O}_4$ ) oxygen ions as shown in Fig. 1 [22]. Between the bipyramid layers, the rare-earth ion layers are stacked along the  $c$  axis. Ferroelectric polarization appears along the  $c$  axis below 875 K and results from electrostatic and size effects that lead to the buckling of  $\text{MnO}_5$  bipyramids and the displacement of the  $\text{Ho}^{3+}$  ions out of the  $(a, b)$  plane [11,22]. The moments of  $\text{Mn}^{3+}$  ions display antiferromagnetic (AF) orderings at  $T_{N,Mn} = 75$  K. The  $\text{Mn}^{3+}$  ions form triangular planar sublattices and the AF exchange coupling among  $\text{Mn}^{3+}$  moments is geometrically frustrated (see Fig. 1). Below  $T_{N,Mn}$ , the Mn magnetic moments order in  $120^\circ$  arrangements [23]. Another transition occurs below 40 K and implies an in-plane Mn spin reorientation by  $90^\circ$  [12,13,23]. Ho moments of the  $4b$  sites are antiferromagnetically coupled within a given layer and  $\text{Ho}^{3+}$  ions display AF orderings at  $T_{N,Ho} = 4.6$  K. It has been proposed that the  $\text{Ho}^{3+}$  moments are oriented along the  $c$  axis with an Ising-type anisotropy. The  $\text{Ho}^{3+}$  ions present in two different crystallographic sites form two sublattices that can order in parallel or antiparallel orientations [24,25]. The  $c$  and  $c = +1/2$  layers are ferromagnetically coupled.

### A. Lattice excitations

The crystal symmetries define the matrix elements of the Raman tensor which are selected by the incident and scattered light polarizations. Thus selection rules define the vibrational modes that can be detected by Raman spectroscopy. The group-theoretical analysis shows that the zone-center phonon modes ( $\Gamma$  point) are in the irreducible representations of the  $C_{6v}$ :  $10A_1 + 5A_2 + 10B_1 + 5B_2 + 15E_1 + 15E_2$ . Only 38 of these modes are Raman active:  $\Gamma_{Raman} = 9A_1 + 14E_1 + 15E_2$ . Using different scattering configurations, it is possible to choose the mode to activate [26]. Here we used the incident wave vector antiparallel to the scattered one (backscattering configuration). The longitudinal optical  $A_1$  modes are activated when the phonon propagation direction corresponds to the direction of the ions displacements using the  $z(xx) = \bar{z}$  polarization configuration. Pure  $E_2$  modes are obtained using  $z(xy) = \bar{z}$  geometry.

Figure 2 presents the Raman spectra measured on  $h$ - $\text{HoMnO}_3$  single crystals with the  $z(xx) = \bar{z}$  and  $z(xy) = \bar{z}$

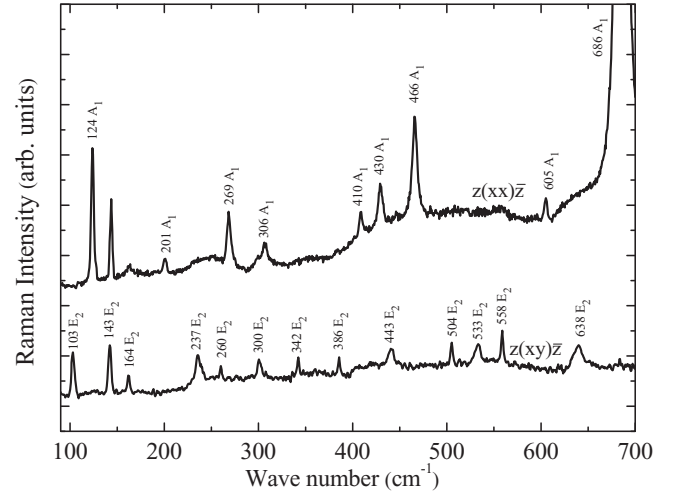


FIG. 2. Phonon modes in  $h$ - $\text{HoMnO}_3$  single crystal observed at 10 K using  $z(xx) = \bar{z}$  ( $A_1$  modes) and  $z(xy) = \bar{z}$  ( $E_2$  modes) scattering configurations.

scattering configurations. The Raman selection rules allow us to identify the 9  $A_1$  modes and 13  $E_2$  modes over 15. The frequencies of the phonon modes at 10 K are reported in Table I and compared to the previous theoretical results on single crystal [18]. We have measured the temperature dependences of the phonon modes in order to identify the effect of the phase transitions.

TABLE I.  $A_1$  and  $E_2$  mode frequencies ( $\text{cm}^{-1}$ ) measured in  $h$ - $\text{HoMnO}_3$  and description of the atomic displacements.

Mode	This work	Theory [18]	Direction of the largest displacement
$A_1$	124	127	$z(\text{Ho})$
	201	234	Rot $x, y(\text{MnO}_5)$
	269	270	$+z(\text{Ho}) - z(\text{Mn})$
	306	295	$x(\text{Mn}), z(\text{O}_3)$
	410	428	$+z(\text{O}_3, \text{O}_4) + x, y(\text{O}_2) - x, y(\text{O}_1)$
	430	460	$+z(\text{O}_4, \text{O}_3) - z(\text{Mn})$
	466	474	$+x, y(\text{O}_1, \text{O}_2), -x, y(\text{Mn})$
	605	614	$+z(\text{O}_1, \text{O}_2) - z(\text{Mn})$
	686	673	$+z(\text{O}_1) - z(\text{O}_2)$
$E_2$		64	$x, y(\text{Ho}, \text{Mn})$
	103	96	$+x, y(\text{Mn}, \text{O}_3, \text{O}_4) - x, y(\text{Ho})$
	143	137	$x, y(\text{Ho})$
	164	152	$x, y(\text{Ho})$
	237	231	$+x, y(\text{Mn}), -x, y(\text{O}_3, \text{O}_4)$
		254	$z(\text{Mn}, \text{O}_2, \text{O}_1)$
	260	265	$z(\text{Mn}, \text{O}_1, \text{O}_2)$
	300	330	$z(\text{O}_2, \text{O}_1), x, y(\text{O}_4)$
	342	339	$+x, y(\text{O}_1, \text{O}_2, \text{O}_3, \text{O}_4) - x, y(\text{Mn})$
	386	402	$+x, y(\text{O}_1, \text{O}_4) - x, y(\text{O}_2, \text{Mn})$
	443	468	$+x, y(\text{O}_4) - x, y(\text{O}_1, \text{Mn})$
	504	523	$x, y(\text{O}_4, \text{O}_3, \text{O}_1, \text{O}_2)$
	533	557	$x, y(\text{O}_4)$
	558	583	$x, y(\text{O}_4, \text{O}_3)$
	638	649	$x, y(\text{O}_3, \text{O}_4)$

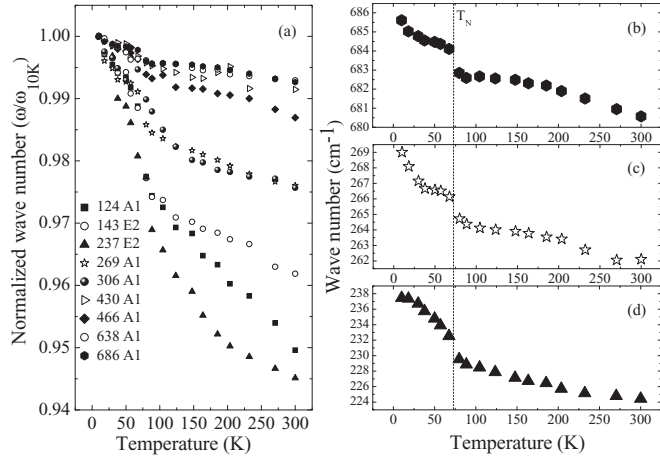


FIG. 3. (a) Normalized wave numbers  $[\omega(T)/\omega(10\text{ K})]$  of 7  $A_1$  and 2  $E_2$  modes and wave numbers of the (b)  $A_1$  mode at  $686\text{ cm}^{-1}$ , (c)  $A_1$  mode at  $269\text{ cm}^{-1}$ , and (d)  $E_2$  mode at  $237\text{ cm}^{-1}$  as a function of temperature.

Figure 3(a) presents the normalized frequencies over the frequency at 10 K of several  $A_1$  and  $E_2$  modes as a function of temperature. All the phonon frequencies soften due to the dilation of the unit cell when temperature increases. Three phonon modes present an abrupt change in their frequencies, as shown in Figs. 3(b)–3(d) as the fingerprint of the spin-phonon coupling in the magnetically ordered phase.

The  $E_2$  mode at  $237\text{ cm}^{-1}$  presents a frequency shift beyond the mean behavior of the other modes [Fig. 3(a)] and an abrupt change of slope around the Néel temperature in Fig. 3(d). This phonon mode is related to the displacement of Mn and O ions in the  $a$ - $b$  plane and it modulates the in-plane Mn-Mn superexchange interaction and the Mn-O-Mn bond angles in the  $a$ - $b$  plane. Such a behavior has already been measured in rare-earth manganites, such as in  $\text{YbMnO}_3$  single crystals [27]. The peaks at  $269$  and  $686\text{ cm}^{-1}$  show the same behavior at the Néel temperature.

The mode at  $269\text{ cm}^{-1}$  is associated to the relative displacement of the apical  $\text{Ho}^{3+}$  ions along the  $c$  direction. The role played by the  $R$  element in the  $\text{RMnO}_3$  manganites has been underestimated. However, the role of the nonmagnetic  $R$  atom is not negligible as underlined by the temperature behavior of the  $\text{Ho}^{3+}$  ions frequency at the Néel temperature.

The mode at  $686\text{ cm}^{-1}$  is related to the relative displacement of the apical oxygen ions along the  $c$  direction and modulates the Mn-O-O-Mn bond angles. Notice that the interplanar coupling between Mn cations and two O anions (Mn-O-O-M) corresponds to the interplanar super-superexchange paths. The abrupt change of slope at  $T_N$  shows that the super-superexchange path through the apical oxygen participates in the three-dimensional magnetic ordering.

### B. Spin excitations

Figure 4(b) shows the low-frequency Raman spectra measured on a  $h$ - $\text{HoMnO}_3$  single crystal at 10 K. Three peaks are measured:  $P_1 = 13\text{ cm}^{-1}$ ,  $P_3 = 25\text{ cm}^{-1}$ ,  $P_2 = 41\text{ cm}^{-1}$  with two polarization configurations. Remember that Raman scattering can probe, in addition to phonon modes, the crystal

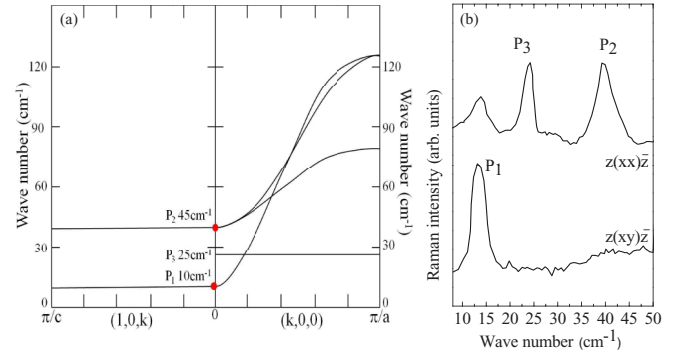


FIG. 4. (a) Magnon dispersions along  $\mathbf{k} = (1,0,k)$  and  $\mathbf{k} = (k,0,0)$  extracted from Ref. [16]. (b) Raman spectra of low-frequency excitations measured at 10 K in  $z(xx)\bar{z}$  and  $z(xy)\bar{z}$  configuration.

field, one magnon (zone-center) excitations, and two-magnon (zone-edge) excitations. Below  $50\text{ cm}^{-1}$ , there are no phonon modes and, as shown in the following paragraph, the  $P_1$ ,  $P_2$ , and  $P_3$  peaks disappear at the Néel temperature, so these peaks can be thus attributed to magnetic excitations. In order to determine the origin of the magnetic excitations, we have compared our measurements to neutron-scattering results. Figure 4(a) represents the magnetic excitation dispersions along the  $\mathbf{k} = (1,0,k)$  and  $\mathbf{k} = (k,0,0)$  axes [16]. At the  $\Gamma$  point, the mode at  $10\text{ cm}^{-1}$  corresponds to the uniaxial anisotropy gap and can be associated to the  $P_1$  peak. The mode at  $45\text{ cm}^{-1}$  in Fig. 4(a) is split at higher energies at the zone edge with a higher branch around  $130\text{ cm}^{-1}$  and a lower branch around  $80\text{ cm}^{-1}$ . The  $P_2$  peak can be attributed to this mode and corresponds to the one-magnon mode of the  $\text{Mn}^{3+}$  magnetic structure in the  $(a,b)$  plane, in particular to the global in-phase and out-of-phase rotations of the  $120^\circ$  pattern inside the basal plane. The  $P_3$  is related to the crystal-field excitation at  $25\text{ cm}^{-1}$ , which presents a flat dispersion as shown by neutron scattering [16]. Transition from the ground state of

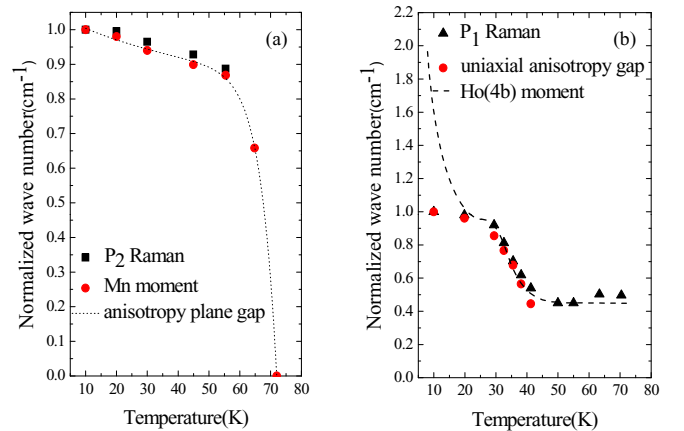


FIG. 5. Temperature dependence of normalized wave number  $[\omega(T)/\omega(10\text{ K})]$  of (a) the magnetic mode  $P_2$  compared with the Mn moments and the energy of the anisotropy plane gap [28], and of (b) the  $P_1$  mode compared to the uniaxial energy gap and the  $\text{Ho}(4b)$  moment [28].



the  $4f$  ions to the excited state are, in principle, Raman active and correspond to crystal-field excitations.

The temperature dependence of the magnon wave number  $P_1$  and  $P_2$  recorded from 10 to 70 K is shown in Fig. 5.

In Fig. 5(a), the Raman shift of the  $P_2$  mode decreases as the temperature is increased. This conventional softening is first compared to the one of the Mn moment. The good agreement with the variation of the Mn moment shows that this magnon mode can be thus associated to the spin excitations of the  $\text{Mn}^{3+}$  ions. It also agrees well with the temperature dependence of the anisotropy plane gap measured by neutron scattering [28]. The  $P_2$  peak is the signature of the anisotropy planar gap in the  $(a,b)$  plane and varies with temperature similar to the  $\text{Mn}^{3+}$  ion moment.

In Fig. 5(b), the  $P_1$  peak wave number presents a change in the slope between 30 and 40 K. We have compared this behavior to the thermal evolution of the uniaxial gap [28]. The good agreement confirms that this peak is related to the uniaxial anisotropy gap. At  $T_{SR} = 33$  K, a Mn-spin-rotation transition has been observed, implying an in-plane Mn-spin reorientation by  $90^\circ$  and an antiferromagnetic order of the Ho

moments along the  $c$  axis. To shed some light on the role of the Ho ions, we have drawn in Fig. 5(b) the temperature dependence of Ho moments. The  $P_1$  peak frequency shift is close to the behavior of the Ho moment down to  $T_{SR}$ . This evidence points out the role of the  $\text{Ho}^{3+}$  ion moment and of the Ho-Mn interaction on the  $P_1$  spin wave. Below  $T_{SR}$ , the uniaxial gap is no longer correlated to the Ho moment. Those measurements show that the exchange-interaction pattern between the rare earth and Mn atoms is a key to understand the uniaxial anisotropy gap but not sufficient below the Mn-spin-rotation transition.

#### IV. CONCLUSION

In summary, our measurements show that the  $E_2$  mode associated to the relative displacement of the apical  $\text{Ho}^{3+}$  ions along the  $c$  direction is sensitive to the the Néel temperature, pointing out the non-negligible role played by the  $R$  element in the  $\text{RMnO}_3$  manganites. We also reveal the spin excitations and the role played by the  $\text{Ho}^{3+}$  ion moment and of the Ho-Mn interaction on the uniaxial anisotropy gap.

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