Spin dynamics in the magnetoelectric effect compound LiCoPO₄

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Inelastic neutron-scattering (INS) experiments were performed to investigate the spin dynamics in magnetoelectric effect LiCoPO₄ single crystals. Weak dispersion was detected in the magnetic excitation spectra along the three principal crystallographic axes measured around the (0 1 0) magnetic reflection. Analysis of the data using linear spin-wave theory indicates that single-ion anisotropy in LiCoPO₄ is as important as the strongest nearest-neighbor exchange coupling. Our results suggest that Co⁴⁺ single-ion anisotropy plays an important role in the spin dynamics of LiCoPO₄ and must be taken into account in understanding its physical properties. High-resolution INS measurements reveal an anomalous low-energy excitation that we hypothesize may be related to the magnetoelectric effect of LiCoPO₄.

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I. INTRODUCTION

LiCoPO₄ is an antiferromagnetic (AFM) insulator belonging to the olivine family of lithium orthophosphates that share the general chemical formula LiMPO₄ (M=Mn²⁺, Fe²⁺, Co²⁺, and Ni²⁺) with 4 formula units per unit cell.¹,² These materials continue to attract much attention due to their exceptionally large magnetoelectric (ME) effect and the anomalies exhibited in the ME coefficients as a function of temperature and magnetic field.³–⁵ To date, it remained an open question whether the anomalies observed in the ME effect of LiMPO₄ are intrinsic due to a particular local environment surrounding the transition-metal ions in LiMPO₄ or due to domain formation structure. The local environment can be slightly distorted in a magnetic (electric) field by virtue of the spin-orbit coupling, giving rise to a collective ferroelectric response (magnetoferroelastic effect).⁶,⁷ The recent domain structure observed by second-harmonic generation (SHG) in LiCoPO₄ was attributed to coexisting AFM and ferrotoroidic domains which may play a role in giving rise to the ME effect.⁸ In addition to the strong ME effect, this family of materials also exhibits intriguing magnetic properties. At low temperatures, LiMPO₄ systems undergo transitions to AFM long-range order (LRO), adopting similar magnetic structures, differing only in spin orientation. For example, with increasing temperature, LiNiPO₄ first undergoes a first-order commensurate-incommensurate (C-IC) phase transition at TN ≈ 20.8 K, changing from a collinear AFM state to a long-range IC order state, followed by a second-order phase transition from long-range IC to short-range IC order at TC = 21.7 K.⁹ On the other hand, LiMnPO₄ undergoes an AFM LRO transition at TN = 34 K as well as a field-induced spin-flop transition.¹⁰ Weak ferromagnetism,¹¹ a ME “butterfly loop” anomaly,¹² and strong magnetic anisotropy have been observed in LiCoPO₄,¹³ which also exhibits the largest ME coefficient among its counterpart compounds, making it of particular interest to study.

LiCoPO₄ crystallizes in an orthorhombic symmetry, space group Pnma (No. 62) at room temperature, with lattice parameters a = 10.093 Å, b = 5.89 Å, and c = 4.705 Å. The structure consists of buckled CoO layers stacked along the crystallographic a axis, and the magnetic Co⁴⁺ (S = 3/2) ions are surrounded by oxygen ions in a strongly distorted CoO₆ octahedral coordination. LiCoPO₄ develops AFM LRO at TN = 21.8 K.¹²,¹⁴ Earlier studies have indicated a simple two-sublattice AFM state below TN with spins aligned along the b axis (whereas LiFePO₄, LiMnPO₄, and LiNiPO₄ have spins oriented along the b, a, and c axes, respectively).²,¹⁵ Figure 1 illustrates the magnetic structure of LiCoPO₄. For simplicity, only the Co²⁺ magnetic ions are shown. As depicted in Fig. 1, different magnetic exchange pathways are at play in this compound. Within the buckled CoO layer, nearest-neighbor

FIG. 1. (Color online) Magnetic unit cell of LiCoPO₄ displaced (0.25 0.25 0) (reciprocal lattice unit) compared to the atomic unit cell. Only the Co²⁺ magnetic ions are shown for clarity. The in-plane (solid) and interplane (dashed) magnetic exchange interactions considered in the spin Hamiltonian [Eq. (1)] are labeled. It is assumed that the spin is oriented strictly along the crystallographic b axis in the model calculation.
Co\(^{2+}\) ions are strongly coupled \((J_1)\) through Co-O-Co superexchange interactions, while additional in-plane magnetic interactions between next-nearest neighbors \((J_2, J_3)\) are mediated through the PO\(_4\) group. Between adjacent layers, the magnetic couplings of nearest-neighbor ions \((J_a, J_b)\) are also mediated via the PO\(_4\) groups. The PO\(_4\) couplings are found to be rather strong and cannot be neglected.\(^9,16\) Due to its layered structure, LiCoPO\(_4\) exhibits properties between two-dimensional (2D) and three-dimensional (3D) magnetic systems.

Although the physical properties of LiCoPO\(_4\) have been studied extensively in the past, there remain a number of puzzles in this compound.\(^17\) Recent magnetoelectric,\(^5,12\) magneto-optic,\(^18\) and magnetic property\(^9,19\) studies do not agree with the originally proposed collinear AFM structure and suggest a more complex magnetic structure for LiCoPO\(_4\). Neutron-diffraction studies suggest the moments in LiCoPO\(_4\) in the AFM phase are not strictly aligned along the \(b\) axis but are uniformly rotated from this axis by a small angle \((\sim 4.6^\circ)\).\(^14\) The observation of weak ferromagnetism and a ME “butterfly loop” anomaly further motivated studies of LiCoPO\(_4\) both experimentally and theoretically.\(^20-22\) In this paper, we report single crystal inelastic neutron-scattering (INS) studies that yield the microscopic magnetic interactions in LiCoPO\(_4\). The data were analyzed within the linear spin-wave approximation using a spin Hamiltonian explicitly including the intraplane and interplane nearest-neighbor, next-nearest-neighbor exchange interactions, and single-ion anisotropy, which are determined in this study.

II. EXPERIMENTAL TECHNIQUES

All measurements reported here were carried out on LiCoPO\(_4\) single crystals. Large crystals were grown for INS experiments by a LiCl flux method similar to that reported in Ref. 23. High-purity starting materials of CoCl\(_2\) (99.999%, MV laboratory), Li\(_2\)PO\(_4\) (99.999% Aldrich), and LiCl (99.999%) were thoroughly ground together at a molar ratio of Li\(_2\)PO\(_4\)+CoCl\(_2\)+LiCl−LiCoPO\(_4\)+3LiCl and sealed in a Pt crucible under Ar atmosphere. Note that the reaction of Li\(_2\)PO\(_4\)+CoCl\(_2\)+LiCl→LiCoPO\(_4\)+3LiCl yields a molar ratio of 1:3 between LiCoPO\(_4\) and the flux material LiCl which we found crucial in growing large LiCoPO\(_4\) single crystals. The mixed powder is premelted at 800 °C and slowly heated to 900 °C. The crucible was maintained at 900 °C for 10 h, then slowly cooled to 640 °C at a cooling rate of 0.7 °C/h, and finally furnace cooled to room temperature. Large purple color LiCoPO\(_4\) single crystals were obtained and extracted by dissolving LiCl in water. The crystals were characterized by x-ray diffraction measurements and found to be of pure single phase. The lattice parameters determined from our neutron-diffraction measurements \(a=10.159, b=5.9,\) and \(c=4.70\) Å at 8 K are in good agreement with prior results.\(^14\)

Two LiCoPO\(_4\) single crystals grown from the same batch were used for the INS experiments. Sample 1, \(m=0.8\) g, and sample 2, \(m=0.4\) g, were oriented in the \((H K 0)\) and \((0 K L)\) scattering planes, respectively. INS experiments were performed using the HB1A triple-axis spectrometer (TAS) at the high flux isotope reactor (HFIR) neutron-scattering facility at Oak Ridge National Laboratory, the BT7 thermal TAS, and the NCNR spin-polarized triple-axis spectrometer (SPINS), cold neutron triple-axis spectrometer at NIST. The magnetic excitations along the \((H 1 0)\) and \((0 K 0)\) directions were measured using the HB1A TAS on sample 1 which was mounted on a thin aluminum disk, sealed in an aluminum sample can, kept under helium atmosphere, and cooled using a closed-cycle He refrigerator. Collimations of 48°-48°-sample-40°-60° downstream from reactor to detector were used throughout the experiment. Constant wave-vector scans were performed at \(T=8\) K (fully ordered state) and \(T=35\) K (well above \(T_N\)). Spin excitations along the \((0 1 L)\) direction were measured using the BT7 TAS at NIST on sample 2. A fixed final energy of \(E_f=14.7\) meV and an open-50°-sample-50°-open collimation were used with pyrolytic graphite [PG(0 0 2)] analyzer crystals in flat mode. High-resolution INS measurements were carried out on sample 1 using the SPINS TAS with a fixed final energy, \(E_f=5\) meV. A collimation of open-80°-sample-80°-open was used with a cold Be filter in the scattering beam. Polarized neutron-scattering experiments were also performed using the BT7 TAS with a fixed final energy of \(E_f=13.7\) meV to clarify the nature of the \(\sim 1.2\) meV low-energy excitation. The polarization analysis technique as applied to this study is discussed in Refs. 24–26. \(^3\) He spin filters (polarizer) are mounted before and after the sample with a spin flipper in the incident beam. The sample is maintained in a horizontal or vertical magnetic field \(\sim 5\) Oe such that the neutron polarization \(\hat{p}\) is parallel to the momentum transfer \(\hat{Q}\); \(\hat{p}\parallel\hat{Q}\) when a horizontal field is applied at the sample position or \(\hat{p}\perp\hat{Q}\) when a vertical magnetic field is applied. With the spin flipper off, we measure the \((++)\) non-spin-flip scattering. On the other hand, with the spin flipper on, the \((++\text{ spin-flip scattering is measured. Sample 2 oriented in the (0 K L) scattering plane and an open-50°-sample-80°-open collimation were used throughout the polarization measurements. Constant wave-vector scans were carried out with both \((++)\) and \((++\text{ configurations. All measurement results have been normalized to a beam monitor count.

III. EXPERIMENTAL RESULTS AND MODELING

Representative constant wave-vector scans with energy transfer between \(h\omega=2.5\) and 8 meV measured using the HB1A and BT7 TAS are shown in Fig. 2. Note that error bars in this paper are statistical in origin and represent one standard deviation. Figure 2(a) shows the temperature dependence of the magnetic excitation measured at \((0 1 0)\). At \(T=8\) K in the fully ordered phase, a single excitation with energy transfer of \(h\omega=4.7\) meV is detected. At a temperature well above \(T_N\) \((T=35\) K) the peak disappears demonstrating the excitation is magnetic in origin. Below \(T_N\), further detailed measurements at \((0 1 0)\) as a function of temperature indicate no significant temperature dependence of this excitation. Figure 2(b) shows the \(T=8\) K constant wave-vector scans measured at \((0 1 0)\) and \((0 1 1.5)\), which typically correspond to the minimum and maximum spin-wave excitations. The data clearly show that the excitation...
observed at $\hbar\omega = 4.7$ meV at (0 1 0) shifts to higher-energy transfer $\hbar\omega = 5.3$ meV at (0 1 1.5) yielding a maximum energy shift of $\sim 0.6$ meV. This indicates that the overall dispersion along the (0 1 L) direction is modest compared to an exchange energy of $kT_N \sim 2$ meV. Similar behaviors were observed for the dispersions along the (0 K 0) and (H 1 0) directions. Note that data in Fig. 2(a) show strong scattering at 2.5 meV, the lowest data point plotted. We will show later that it is from scattering of a low-energy excitation at $\sim 1.2$ meV which has been observed in recent SPINS high-resolution measurements.

To determine the magnetic excitation spectra along all three principal axis directions, a series of constant wave-vector scans was carried out in the (H K 0) and (0 K L) scattering planes at $T=8$ K around the (0 1 0) magnetic reflection. Figure 3 depicts the ground-state magnetic dispersion relations along the (H 1 0), (0 K 0), and (0 1 L) directions constructed from energy scans at constant wave vector. We determined the peak positions assuming the Gaussian peak shapes that were fit to each of the constant wave-vector scans measured. For both the HB1A and BT7 triple-axis spectrometers, the energy resolution at the elastic position was $\Delta E = 1$ meV. The experimental uncertainties had a significant effect in the theoretical modeling as described in the text below. The measured spectra indicate a spin-wave excitation of $\hbar\omega = 4.7 \pm 0.24$ meV at (0 1 0) which vanishes abruptly above $T_N$, while modest dispersion was observed along all three principal symmetry directions with the scale in Fig. 3 being chosen to best exhibit the dispersion that falls within a band of $0.8$ meV. This relatively weak dispersion suggests an Ising-type model in LiCoPO$_4$: in a pure Ising model the magnetic excitations are completely dispersionless.

To analyze the measured spin-wave dispersion curves of LiCoPO$_4$ using linear spin-wave theory, we consider the different magnetic exchange interactions as illustrated in Fig. 1 and assume an AFM ground state with spins pointing strictly along the b axis. Taking into account the intraplane and interplane nearest neighbor, next-nearest-neighbor interactions, and the single-ion anisotropy, the spin Hamiltonian can be expressed in the following form:

$$\mathcal{H} = \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{i,\alpha} D_\alpha (S_i^\alpha)^2, \quad (1)$$

where $D_\alpha$ (\(\alpha=x, y, z\)) represents the single-ion anisotropy along the x, y, and z directions. In order to have the spins pointing along the z axis in the model calculation, the Cartesian coordinate x, y, and z directions are defined to be along the crystallographic a, c, and b directions, respectively. The zero point of the energy spectrum is chosen such that $D_z = 0$. Within a linear spin-wave approximation, the derived spin-wave dispersion from Eq. (1) is given by

$$\hbar\omega = \sqrt{A^2 - (B \pm C)^2}, \quad (2)$$

where

FIG. 2. (Color online) Representative constant wave-vector scans plotted as scattering intensity versus energy transfer between $\hbar\omega = 2.5$ and 8 meV. (a) Temperature dependence of the $\sim 4.7$ meV excitation measured at (0 1 0) at $T=8$ and 35 K using the HB1A TAS. (b) $T=8$ K constant wave-vector scans using the BT7 TAS measured at (0 1 0) and (0 1 1.5) showing a single magnetic excitation that exhibits modest but unambiguous dispersion along the (0 1 L) direction. Intensities were normalized to the incident neutron flux by counting against neutron monitor counts.

FIG. 3. (Color online) Spin-wave dispersion curves along three reciprocal directions constructed from a series constant wave-vector scans measured at $T=8$ K. Data points are obtained based upon a Gaussian peak approximation. The solid and dash lines are calculations based on a global fit to the linear spin-wave approximation theory as described in the text.
\[ A = 4S(J_1 + J_3) - 2S[J_2[1 - \cos(\mathbf{q} \cdot \mathbf{r}_3)] + J_3[1 - \cos(\mathbf{q} \cdot \mathbf{r}_4)] + J_4[2 - \cos(\mathbf{q} \cdot \mathbf{r}_7) - \cos(\mathbf{q} \cdot \mathbf{r}_8)] + D_3s + D_4s, \]
\[ B = D_3s - D_4s, \]
\[ C = 2J_3[\cos(\mathbf{q} \cdot \mathbf{r}_1) + \cos(\mathbf{q} \cdot \mathbf{r}_2)] \]
\[ + 2J_4[\cos(\mathbf{q} \cdot \mathbf{r}_3) + \cos(\mathbf{q} \cdot \mathbf{r}_4)], \]
and \( \mathbf{r}_i \) denotes the vectors directed between two Co\(^{2+} \) ions,
\[ \mathbf{r}_1 = (0,b/2,c/2), \quad \mathbf{r}_2 = (0,b/2,-c/2), \]
\[ \mathbf{r}_3 = (a/2,b/2,0), \quad \mathbf{r}_4 = (a/2,-b/2,0), \]
\[ \mathbf{r}_5 = (0,b,0), \quad \mathbf{r}_6 = (0,0,c), \]
\[ \mathbf{r}_7 = (a/2,0,c/2), \quad \mathbf{r}_8 = (a/2,0,-c/2). \]

Nonlinear-least-squares fits of the spin-wave dispersion expressed by Eq. (2) to the observed magnetic spectra yields the following: \( J_1 = 0.743 \pm 0.187 \) meV, \( J_2 = 0.105 \pm 0.159 \) meV, \( J_3 = 0.194 \pm 0.131 \) meV, \( J_4 = -0.163 \pm 0.08 \) meV, \( J_5 = -0.181 \pm 0.125 \) meV, \( D_3 = 0.718 \pm 0.192 \) meV, and \( D_4 = 0.802 \pm 0.208 \) meV. The obtained microscopic interaction parameter \( J_1 \) is significantly larger than \( J_4 \) and \( J_5 \), consistent with previous observations that the magnetic behavior of LiCoPO\(_4\) is intermediate between 2D and 3D systems. Moreover, the obtained positive value of \( J_1 \) indicates in-plane AFM nearest-neighbor coupling, whereas negative \( J_4 \) and \( J_5 \) values suggest interplane ferromagnetic (FM) coupling along the \( a \) axis consistent with the magnetic structure, where the magnetic unit cell is doubled along the \( b \) and \( c \) axes but not along the \( a \) axis. \( J_2 \) and \( J_3 \) have the same sign as \( J_1 \), indicating that they compete with \( J_1 \) and may cause frustration; however, they are relatively weak compared to \( J_1 \). \( J_2/J_1 = 0.14 \) and \( J_3/J_1 = 0.26 \). Both \( D_3 \) and \( D_4 \) are positive, favoring a ground state with the magnetic moment along the \( b \) axis consistent with the elastic magnetic neutron-scattering results. An important result in our study is the large values of the single-ion anisotropy compared to the nearest-neighbor coupling \( D_3 \sim D_4 \sim J_1 \). Although strong single-ion anisotropy in LiCoPO\(_4\) has been suggested by several models,\(^5,^{27}\) this study provides experimental evidence that the single-ion anisotropy is as important as the strongest magnetic exchange interaction in LiCoPO\(_4\). Such relatively strong anisotropy may split the \( \pm 3/2 \) quartet of the Co\(^{3+} \) ion into two doublets, rendering the suggested Ising-type character to LiCoPO\(_4\).\(^4\)

The “±” sign in Eq. (2) (\( B \leq C \)) indicates that there are two nondegenerate spin-wave branches which come directly from the different values of \( D_3 \) and \( D_4 \). Using the obtained best-fit parameters, the calculated dispersion curves of the two branches are plotted as solid lines (“\( B-C \)” branch) and dash lines (“\( B+C \)” branch) in Fig. 3. The two calculated spin-wave branches predict a maximum separation of \( \sim 0.3 \) meV at \( (0 \, 1 \, 0) \), \( (1 \, 1 \, 0) \), and \( (0 \, 1 \, 1) \). In the thermal neutron TAS measurements using HB1A and BT7 with a resolution of \( \sim 1 \) meV, only one excitation was observed at these wave vectors. We have two high-resolution measure-
ments using SPINS TAS, fixed \( \hbar \omega = 5 \) meV with a resolution of \( \sim 0.28 \) meV at \( (1 \, 1 \, 0) \) and \( (0 \, 1 \, 0) \) with energy transfer up to 8 meV. The constant wave-vector scan at \( (0 \, 1 \, 0) \) at \( T = 9 \) K is shown in Fig. 4(a). At \( (0 \, 1 \, 0) \), where the model predicts the maximum separation between these two branches, only one excitation around \( \sim 4.7 \) meV is observed. The additional low-energy excitation observed at \( \sim 1.2 \) meV does not agree with the model and is discussed below. Our results could not resolve the two branches for two possible reasons. First, the second excitation may be very weak in intensity, and our model does not predict intensities. Second, the intrinsic linewidth of the observed excitations are broader than the resolution (\( \sim 1 \) meV) suggestive of contributions from both branches overlap and cause the broadening.

High-resolution measurements on SPINS show an anomalous low-energy excitation below \( T_N \) that does not fit in the linear spin-wave model. Figure 4(a) depicts the \( T = 9, 15, \) and \( 21 \) K data measured at \( (0 \, 1 \, 0) \). In addition to the \( \hbar \omega = 4.7 \) meV excitation, the \( T = 9 \) K SPINS data clearly show a low-energy excitation at \( \hbar \omega = 1.2 \) meV. The peak position of this excitation is practically temperature independent, but the peak intensity decreases with increasing temperature and eventually the peak vanishes above \( T_N \). It also shows weak dispersion along all three reciprocal directions. Figure 4(b) shows constant wave-vector scans measured along the \( (0 \, K \, 0) \) direction at \( 9 \) K. Very weak dispersion was ob-
The spin dynamics of the ME compound LiCoPO$_4$ were determined by inelastic neutron-scattering experiments. Similar to LiNiPO$_4$, LiMnPO$_4$, and LiFePO$_4$, the observed magnetic excitation spectra in LiCoPO$_4$ can be adequately described by a linear spin-wave theory. Our results indicate that single-ion anisotropy is as important as the strong nearest-neighbor magnetic coupling and plays an essential role in understanding the spin structure and dynamics of LiCoPO$_4$. However, the observation of the second dispersionless low-energy $\sim$1.2 meV magnetic excitation is unusual and is not contained in the spin-wave Hamiltonian, suggesting that it may be closely related to the strong ME effect in LiCoPO$_4$. The nature of this excitation is not understood yet and requires further detailed studies.

IV. SUMMARY

The spin dynamics of the ME compound LiCoPO$_4$ were determined by inelastic neutron-scattering experiments. Similar to LiNiPO$_4$, LiMnPO$_4$, and LiFePO$_4$, the observed magnetic excitation spectra in LiCoPO$_4$ can be adequately described by a linear spin-wave theory. Our results indicate that single-ion anisotropy is as important as the strong nearest-neighbor magnetic coupling and plays an essential role in understanding the spin structure and dynamics of LiCoPO$_4$. However, the observation of the second dispersionless low-energy $\sim$1.2 meV magnetic excitation is unusual and is not contained in the spin-wave Hamiltonian, suggesting that it may be closely related to the strong ME effect in LiCoPO$_4$. The nature of this excitation is not understood yet and requires further detailed studies.

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FIG. 5. (Color online) BT7 polarized neutron data measured at \((0.1 2 0)\) in the horizontal field configuration, \(\hat{p} \parallel \mathbf{Q}\). (a) Comparison of spin-flip \((-\leftrightarrow)\) and non-spin-flip \((\leftrightarrow)\) scatterings measured at \(T = 7\) K indicating the magnetic origin of the second low-energy excitation. Inset: spin-flip \((-\leftrightarrow)\) and non-spin-flip \((\leftrightarrow)\) scatterings of the nuclear reflection \((0 2 0)\). (b) Comparison of SPINS high-resolution data and the BT7 subtracted polarized data; the non-spin-flip \((\leftrightarrow)\) data were subtracted from the spin-flip \((-\leftrightarrow)\) data.
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