

Ferrimagnetism and spin reorientation in the high-pressure double double perovskites CaMnCrSbO_6 and CaMnFeSbO_6

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Two CaMnBSbO_6 ($B = \text{Cr}$ and Fe) high-pressure double double perovskites are reported. Spins in CaMnCrSbO_6 order below $T_C = 49$ K into a collinear ferrimagnetic arrangement with spins in the xy plane. CaMnFeSbO_6 has the same ordered magnetic structure below $T_{C1} = 55$ K, but also shows a second magnetic transition at $T_{C2} = 21$ K where the spins reorient towards the z axis. This may reflect a greater degree of magnetic disorder for $B = \text{Fe}$ and A - B intersite charge transfer may also be significant.

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I. INTRODUCTION

Compounds of general formula ABO_3 with the perovskite structure accept a wide range of A and B site cations, and can give rise to $AA'B_2O_6$ or $A_2BB'O_6$ double perovskites [1]. However, the combination of cation order into both sublattices is uncommon. Among the nine possible double double (doubly ordered) $AA'BB'O_6$ structures [2], only those combining rocksalt order of B -site cations with layered [3,4] or columnar A cation order have been reported. The latter type was recently reported for MnRMnSbO_6 ($R = \text{rare earth}$) [5,6] and CaMnBRReO_6 ($B = \text{transition metal}$) [7,8] compositions. Both systems show a rich variety of magnetic properties. The rare earth materials show multiple magnetic transitions and have strong magnetic anisotropy [6]. CaMnFeReO_6 has robust $\text{Fe}^{3+}/\text{Re}^{5+}$ ferrimagnetic order at ~ 500 K and exhibits negative magnetoresistance at low temperatures [7]. $\text{CaMnB}^{2+}\text{Re}^{6+}\text{O}_6$ are ferrimagnetic for $B = \text{Co}^{2+}$, ferromagnetic for $B = \text{Ni}^{2+}$ [8], and two perpendicular spin sublattices for A and B site cations are reported for antiferromagnetic $B = \text{Mn}^{2+}$ [7].

A recent study of compositions between $\text{Ca}_2\text{FeReO}_6$ [9,10] and $\text{Mn}_2\text{FeReO}_6$ [11,12] revealed little miscibility between the double perovskite end members and the double double perovskite CaMnFeReO_6 formed at the midpoint of the series [13]. However, a coherent evolution of magnetic properties with high- T_C Fe-Re spin order and low temperature magnetic order of Mn^{2+} spins was observed throughout. The Ca_2BSbO_6 and Mn_2BSbO_6 ($B = \text{Cr, Fe}$) double perovskites, however, show different magnetic behaviors, with strong frustration in the Ca-based materials leading to low temperature ferromagnetism ($B = \text{Cr}$) and spin-glass behavior ($B = \text{Fe}$) [14,15], while the high-pressure Mn analogs show antiferromagnetism with a helical spin order for $B = \text{Fe}$ below 60 K [16,17]. We have thus investigated the double double perovskites formed

between these two pairs and we report here the structures and magnetic properties of the two high-pressure double double perovskite oxides CaMnBSbO_6 ($B = \text{Cr}$ and Fe).

II. EXPERIMENT

Polycrystalline CaMnBSbO_6 samples were synthesized under high-pressure and high-temperature conditions. The precursors were prepared by mixing stoichiometric proportions of CaMnO_3 , Cr_2O_3 and Sb_2O_3 for CaMnCrSbO_6 , and $\text{Ca}_2\text{Fe}_2\text{O}_5$, MnO and Sb_2O_5 for CaMnFeSbO_6 . CaMnO_3 was prepared by heating stoichiometric amounts of CaCO_3 and MnO at 1200 °C under a N_2 flow in increasing temperature steps, and $\text{Ca}_2\text{Fe}_2\text{O}_5$ was made by heating CaCO_3 and Fe_2O_3 at 1200 °C. The precursor mixtures were packed into Pt capsules and compressed to 10 GPa using a Walker-type multianvil press. Samples were heated at 1100 °C for 20 min and quenched, after which pressure was slowly released.

Powder x-ray diffraction was used to confirm that double double perovskites were formed in both samples. Neutron powder diffraction (NPD) data were collected for ~ 50 mg samples using the D20 beamline at the Institut Laue-Langevin (Grenoble, France). The $0 < 2\theta < 130^\circ$ angular range was covered with a 0.1° step size. Long scans were taken at 1.5, 65, and 300 K for CaMnCrSbO_6 using wavelength $\lambda = 1.87 \text{ \AA}$ and at 3, 35, and 70 K for CaMnFeSbO_6 using $\lambda = 2.41 \text{ \AA}$ for refinement of their nuclear and magnetic structures. A scan in high resolution mode was also collected at 300 K for CaMnFeSbO_6 using $\lambda = 1.54 \text{ \AA}$. Additional short scans were collected from 5 to 65 K every 1.2 K for CaMnFeSbO_6 to study the thermal evolution of magnetic structure through the two discovered magnetic transitions. The magnetic symmetry analysis was performed using BASIREPS [18] and the diffraction patterns were fitted through the Rietveld method using the FULLPROF package [19]. Magnetization measurements were made using a MPMS Quantum Design magnetometer. Temperature dependence of the magnetization was scanned in field cooled (FC) and zero field cooled (ZFC) modes.

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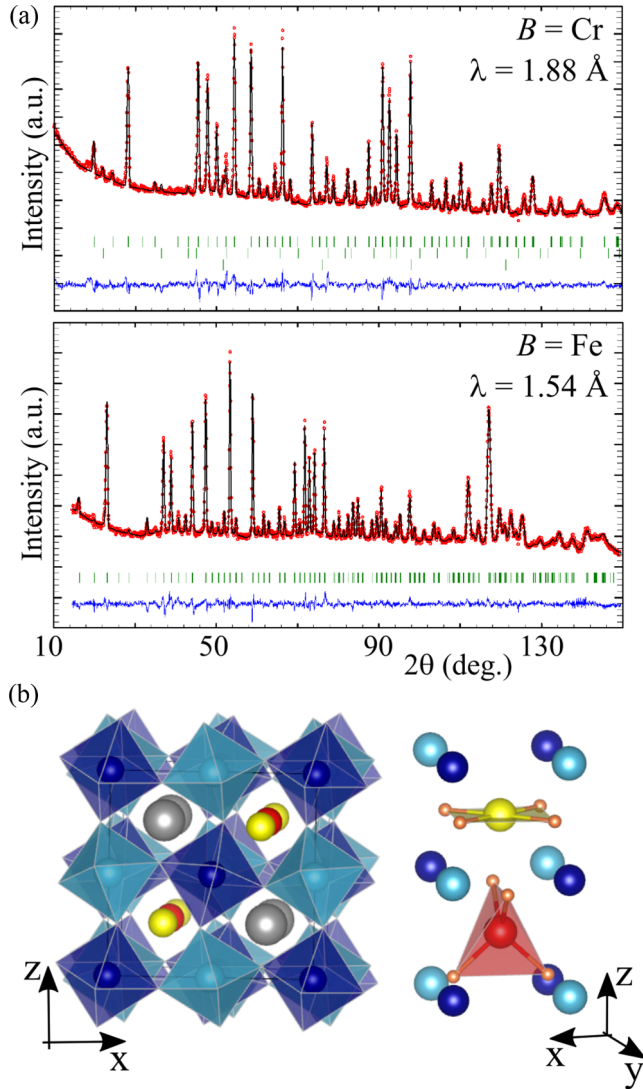


FIG. 1. (a) Rietveld fits of the double double perovskite CaMnBSbO_6 structures against 300-K NPD data. Top, $B = \text{Cr}$, secondary phase markers are for MnCr_2O_4 and V (sample holder); bottom, $B = \text{Fe}$. (b) $P4_2/n$ CaMnBSbO_6 double double perovskite structure, with a view of the Mn'/Mn'' A-site column to the right (A-cation $\text{Ca}/\text{Mn}'/\text{Mn}'' = \text{grey}/\text{red}/\text{yellow}$; BO_6/SbO_6 octahedra = blue/cyan).

III. RESULTS AND DISCUSSION

A. Crystal structures

Fits to 300-K NPD data (Fig. 1) confirm that CaMnCrSbO_6 and CaMnFeSbO_6 adopt double double perovskite structures in space group $P4_2/n$. The relative values of cell parameters are consistent with the larger ionic radius of Fe^{3+} (0.745 Å) compared to Cr^{3+} (0.715 Å) [20]. The neutron scattering lengths of Ca, Mn, Cr/Fe, and Sb (4.70, -3.73 , $3.64/9.45$, and 5.57 fm respectively) provide a good contrast allowing precise occupancies to be refined. The Ca site was found to be fully occupied but cation mixing was observed at all other sites, as shown in Table I. Partial B occupation is observed at both the tetrahedral Mn' ($2a$) and square planar Mn'' ($2b$) sites within the A-site Mn column. The refined occupan-

cies suggest a preference of Fe at the square planar (20.4%) over the tetrahedral environment of A' (8.0%). The same site preference was observed for Co and Ni in the CaMnBReO_6 ($B = \text{Co}, \text{Ni}$) analogs [8]. However Cr shows no preference with almost 20% substitution at both Mn sites. 5% B/Sb antisite disorder is observed for $B = \text{Cr}$, but $B = \text{Fe}$ is more disordered with 13% inversion. Overall refined compositions are $\text{CaMn}_{0.81}\text{Cr}_{1.19}\text{SbO}_6$ and $\text{CaMn}_{0.85}\text{Fe}_{1.15}\text{SbO}_6$, showing that both materials are slightly Mn deficient. Secondary phase MnCr_2O_4 spinel [21] (0.2%) is observed in the $B = \text{Cr}$ fit (Fig. 1).

Formal cation charges estimated using bond valence sums (BVS's) from bond distances as shown in Table I are consistent with the nominal distribution $\text{Ca}^{2+}\text{Mn}^{2+}\text{B}^{3+}\text{Sb}^{5+}\text{O}_6$. Deviations such as apparent underbonding of the Mn sites reflect the cation disorder and strained nature of these quenched high-pressure materials. The tendency for d^{10} Sb^{5+} to displace off center is evidenced by a relatively high octahedral distortion factor Δ in the $B = \text{Cr}$ structure, whereas the greater level of antisite disorder for $B = \text{Fe}$ leads to a very regular average Sb/FeO_6 octahedron with small Δ . Ca sits in the large cuboctahedral void with a tenfold coordination and all Ca-O distances between 2.36 and 2.80 Å, in good agreement with the typical bond lengths for Ca in other double double perovskites [7,8,13].

Octahedral tilt angles calculated from the $B\text{-O-Sb}$ bond angles are $\phi = 14.8(1)/17.1(1)^\circ$ from the z axis and $\theta = 16.5(1)/16.6(1)^\circ$ within the xy plane for $B = \text{Cr}/\text{Fe}$. These values lie within the range $15\text{--}20^\circ$ observed in the MnRMnSbO_6 double double perovskite series [5]. These substantial tilts stabilize the columnar order of isovalent Ca and Mn cations within the A sites of the double double structure.

B. Magnetic properties

Magnetic susceptibility measurements for CaMnBSbO_6 ($B = \text{Cr}, \text{Fe}$) samples are shown in Fig. 2. Curie-Weiss fits to the paramagnetic regions give paramagnetic moments of $7.45 \mu_B$ and $7.59 \mu_B$ for Cr and Fe samples respectively. Predicted spin-only moments are $7.07 \mu_B$ and $8.36 \mu_B$; the poor agreement for $B = \text{Fe}$ reflects the observed nonlinearity of inverse susceptibility in the paramagnetic regime, which may result from the presence of magnetic impurities. Fitted Weiss constants of $\theta = -120$ and -36 K for $B = \text{Cr}$ and Fe show that dominant couplings between Mn and B spin sublattices are antiferromagnetic, as expected from Goodenough-Kanamori-Anderson (GKA) rules for their superexchange interactions [23], and in keeping with their low-temperature ferrimagnetic orders described below. The susceptibility data show a single ferrimagnetic Curie transition for CaMnCrSbO_6 at $T_C = 49$ K, but two magnetic transitions are observed for CaMnFeSbO_6 , at $T_{C1} = 55$ and $T_{C2} = 21$ K.

The magnetization-field loop for CaMnCrSbO_6 at 2 K shows a magnetization of $1.55 \mu_B$ at zero field increasing to $1.77 \mu_B$ at 4 T, consistent with the expected value of $2 \mu_B$ for ferrimagnetic order of antiparallel Mn^{2+} $S = 5/2$ and Cr^{3+} $S = 3/2$ spins. Loops for the Fe analog at 2 and 25 K are very similar showing that the type of magnetic order does not change at $T_{C2} = 21$ K. The coercive field of 0.2 T at 2 K shows that CaMnFeSbO_6 has appreciable magnetic anisotropy. An

TABLE I. Atomic coordinates and interatomic distances (d in Å) for CaMnBSbO₆ from the Rietveld fits of 300-K NPD data using tetragonal space group $P4_2/n$. Lattice parameters $a = 7.6320(2)/7.6616(1)$ Å and $c = 7.6208(4)/7.6443(3)$ Å. Fitting reliability factors: $R_p = 2.11/1.69\%$, $R_{wp} = 3.02/2.23\%$, $R_f = 5.44/3.51\%$, $R_B = 7.80/5.60\%$, $\chi^2 = 7.17/3.32$. Upper/lower or left/right values correspond to $B = \text{Cr/Fe}$.

Site (Wyckoff)	x	y	z	occ	$B_{\text{iso}}(\text{Å}^2)$	BVS ^a
Mn ¹ /B (2a)	0.75	0.75	0.75	0.81/0.19(1)	1.6(3)	1.82
				0.912/0.088(3)	0.01(1)	1.59
Mn ² /B (2b)	0.25	0.25	0.75	0.82/0.18(1)	1.6	1.33
				0.784/0.216(4)	0.01	1.27
Ca (4e)	0.25	0.75	0.7799(9)	1.0	2.8(1)	2.08
			0.7786(8)		0.7(1)	2.05
B/Sb (4c)	0	0.5	0.5	0.952/0.048(5)	0.64(8)	2.78
				0.87/0.13(1)	0.01	2.49
Sb/B (4d)	0	0	0.5	0.952/0.048(5)	0.64	5.79
				0.87/0.13(1)	0.01	4.92
O1 (8g)	-0.041(1)	0.552(1)	0.2396(9)	1.0	1.26(4)	
	-0.053(2)	0.555(1)	0.244(1)		0.14(2)	
O2 (8g)	-0.252(2)	-0.0502(6)	0.5643(5)	1.0	1.26	
	-0.244(2)	-0.0478(5)	0.5653(4)		0.14	
O3 (8g)	-0.252(2)	0.0573(6)	-0.0345(7)	1.0	1.26	
	-0.252(2)	0.0586(4)	-0.0345(4)		0.14	
$d_{\text{B-O1}}(\times 2)$	2.048(8)/2.04(1)	$d_{\text{Sb-O1}}(\times 2)$	1.895(8)/1.96(1)	$d_{\text{Ca-O1}}(\times 2)$	2.70(1)/2.77(1)	
$d_{\text{B-O2}}(\times 2)$	1.99(1)/2.06(1)	$d_{\text{Sb-O2}}(\times 2)$	2.02(1)/1.97(1)	$d_{\text{Ca-O1}}(\times 2)$	2.80(1)/2.79(1)	
$d_{\text{B-O3}}(\times 2)$	1.99(1)/2.00(1)	$d_{\text{Sb-O3}}(\times 2)$	1.96(1)/1.97(1)	$d_{\text{Ca-O2}}(\times 2)$	2.590(7)/2.575(5)	
$\langle d_{\text{B-O}} \rangle$	2.01(1)/2.03(1)	$\langle d_{\text{Sb-O}} \rangle$	1.96(1)/1.97(1)	$d_{\text{Ca-O3}}(\times 2)$	2.45(1)/2.445(7)	
$\Delta[\text{BO}_6] \times 10^{4b}$	1.85/1.53	$\Delta[\text{SbO}_6] \times 10^{4b}$	6.79/0.08	$d_{\text{Ca-O3}}(\times 2)$	2.36(1)/2.373(7)	
$d_{\text{Mn}^{\prime\prime}\text{-O}}(\times 4)$	2.080(5)/2.097(4)	$d_{\text{Mn}^{\prime\prime}\text{-O}}(\times 4)$	2.20(1)/2.13(1)	$\langle d_{\text{Ca-O}} \rangle$	2.58(1)/2.59(1)	

^aBVS values estimated from interatomic distances as $V_i = \sum_j S_{ij} i = \exp(r_0 - r_{ij}/0.37)$, using R_0 values 1.79, 1.967, 1.724, 1.734, and 1.942 for Mn²⁺, Ca²⁺, Cr³⁺, Fe³⁺, and Sb⁵⁺ respectively [22].

^b Δ is the octahedral distortion calculated from bond lengths as $\Delta = 1/6 \sum [(d_i - d_{\text{Av}})/d_{\text{Av}}]^2$.

ideal ferrimagnetic order of Mn²⁺ and Fe³⁺ $S = 5/2$ spins would lead to zero net moment. The small $0.4 \mu_B$ observed moment, increasing to $0.94 \mu_B$ at 7 T, likely reflects cation disorder, in particular the 13% Fe/Sb cation inversion at the B sites.

NPD patterns recorded below the Curie transitions reveal magnetic diffraction peaks that index with propagation vector $k = [000]$, and the resulting magnetic symmetry analysis for the CaMnBSbO₆ phases is summarized in Table II. The magnetic intensities in the 1.5–65-K NPD difference pattern for CaMnCrSbO₆ are fitted by irreducible representation (Irep) Γ_3 with moments in the xy plane. The refined magnetic moments of $3.72(3)\mu_B$ and $2.82(3)\mu_B$ respectively at Mn²⁺ (with tetrahedral and square-planar site values constrained to be equal) and Cr³⁺ sites are reduced from ideal spin-only values of $5 \mu_B$ and $3 \mu_B$ due to cation disorder and frustration. This model corresponds to the simple ferrimagnetic arrangement expected from the magnetization data, and is shown in Fig. 3(a) with the final fit to the magnetic diffraction intensities in Fig. 3(b).

At 35 K, below the first magnetic transition at $T_{C1} = 55$ K, CaMnFeSbO₆ shows the same spin arrangement as for CaMnCrSbO₆, with magnetic moments of $3.00(4)\mu_B$ and $2.17(3)\mu_B$ for Mn²⁺ and Fe³⁺ respectively. Changes to the magnetic diffraction intensities are observed on cooling through the second transition ($T_{C2} = 21$ K) to 3 K, as shown in Fig. 4. Fits to the 3–70-K NPD magnetic intensities reveal that additional spin components parallel to the z axis

that follow the Γ_1 Irep are present. The T_{C2} transition thus corresponds to a spin reorientation out of the xy plane, as shown in Fig. 4(a). The total refined magnetic moments of $3.89(6)\mu_B$ and $2.78(15)\mu_B$ for Mn²⁺ and Fe³⁺ respectively at 3 K (Table III) show that the Fe value is somewhat reduced from the ideal value of $5 \mu_B$, again reflecting the Fe/Sb antisite disorder.

Fits to the short neutron scans for CaMnFeSbO₆ were used to extract the temperature dependences of the magnetic moments as shown in Fig. 5. Critical fits shown on Fig. 5(a) confirm that the μ_z components disorder at $T_{C2} = 22(1)$ K for exponent $\beta = 0.35(2)$ while μ_x components decrease to zero at $T_{C1} = 52.1(3)$ K for $\beta = 0.4(1)$. The critical exponents are in agreement with the theoretical value of $\beta = 0.365$ for a three-dimensional Heisenberg magnet.

The spin reorientation transition at $T_{C2} = 21$ K is likely driven by magnetic anisotropy effects which are evidenced by the moderate coercivity of 0.2 T at 2 K in magnetization data [Fig. 2(b)]. The tilt of the Fe spin directions out of the xy plane (33° at 3 K) observed by NPD is of comparable magnitude to the FeO₆ octahedral tilting angle of $\phi = 17^\circ$ measured in the crystal structure analysis. However, the octahedral tilts from the c axis are out of phase [Fig. 1(b); the overall tilt scheme is $a^+ a^+ c^-$ in Glazer notation [5]] with half of the octahedra tilted by $+\phi$ and the other half by $-\phi$. All Fe moments are parallel so only half are tilted in the same direction as their FeO₆ octahedra, hence there is an equivalent anisotropy-stabilized magnetic ground state in which μ_z

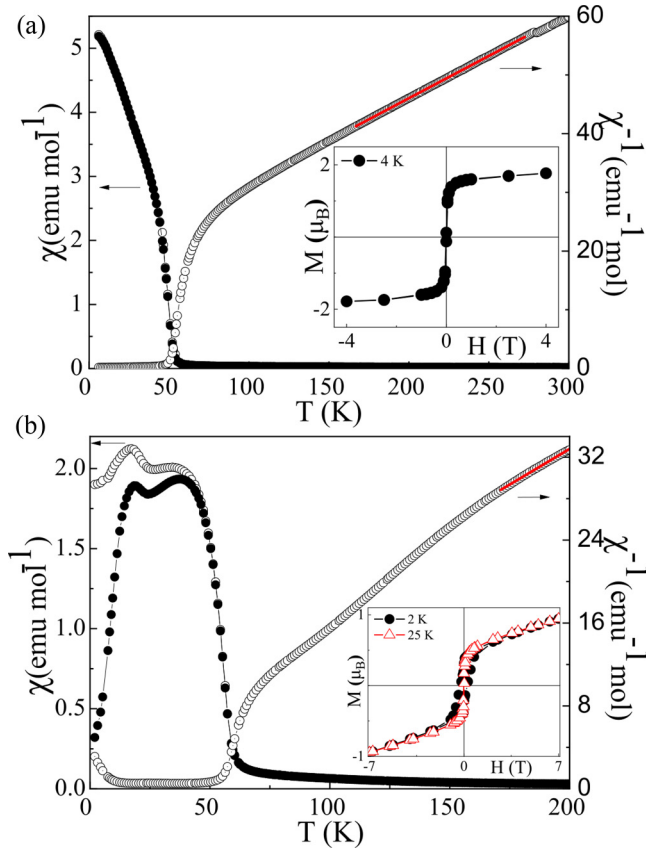


FIG. 2. Magnetic susceptibility and hysteresis loops (insets) for CaMnBSbO_6 ; (a) $B = \text{Cr}$ and (b) $B = \text{Fe}$. Curie-Weiss fits to inverse susceptibilities are also shown.

components are reversed relative to the directions shown in Fig. 4(a) (lower right). Thermal fluctuations between these two states on warming likely lead to the spin reorientation transition at $T_{C2} = 21$ K above which μ_z components become dynamic with static components only present in the xy plane up to $T_{C1} = 55$ K.

Although second magnetic transitions below T_C have been observed in other double double perovskites, these have been due to low-temperature orders of other spin sublattices, of Nd^{3+} moments in MnNdMnSbO_6 [5], and of Mn spins in CaMnBReO_6 ($B = \text{Mn}, \text{Fe}$) [7]. In CaMnFeSbO_6 , both Mn^{2+} and Fe^{3+} spins order at $T_{C1} = 55$ and reorient below $T_{C2} = 21$ K. It is surprising that the Fe phase shows a spin reorientation transition whereas the Cr analog does not, as both $B = \text{Cr}^{3+}$ and Fe^{3+} cations have nondegenerate ground states.

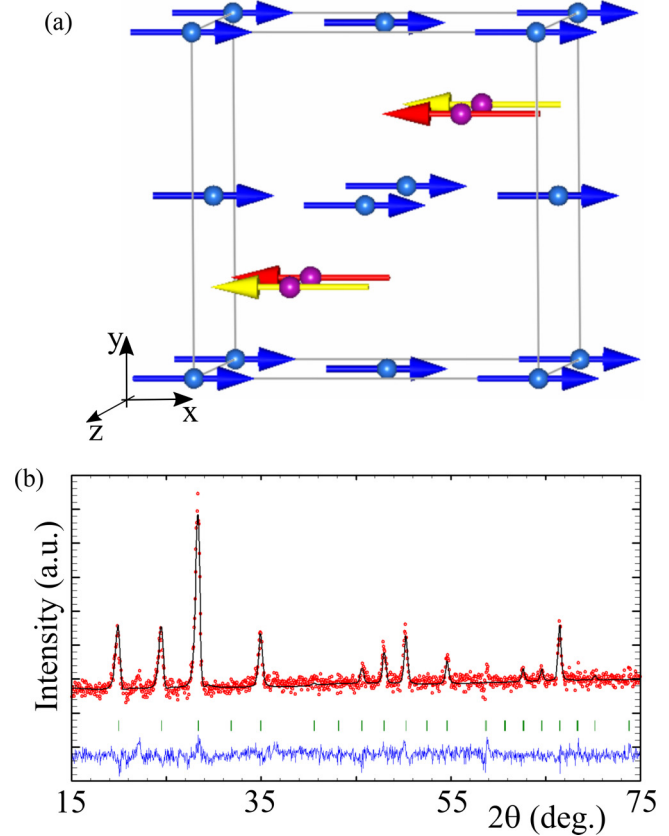


FIG. 3. Magnetic structure determination for CaMnCrSbO_6 . (a) Spin structure where red/yellow/blue arrows represent, $\text{Mn}'/\text{Mn}''/B = \text{Cr}$ site spins. (b) Rietveld fit to the 1.5–65-K NPD difference pattern. The first three magnetic peaks (observed in the range $2\theta = 15\text{--}30^\circ$) are $(110)/(101)$, (111) , and $(200)/(002)$.

This is not likely to be due to structural effects of differing degrees of B/Sb antisite cation disorder, as $B = \text{Cr}$ has less (5%) disorder than $B = \text{Fe}$ (13%), and greater disorder would be more likely to suppress a coherent rotation of spin directions. The spin rotation may reflect the greater magnetic disorder for $B = \text{Fe}$ due to the larger B/Sb antisite disorder, as the saturated low-temperature B -site moment of $2.8 \mu_B$ is substantially below the ideal value of $5 \mu_B$ for Fe^{3+} , whereas the $2.8 \mu_B$ value for $B = \text{Cr}$ is close to the ideal $3 \mu_B$ Cr^{3+} moment. Charge transfer between A -site $\text{Mn}^{2+}/\text{Fe}^{2+}$ and B^{3+} cations for $B = \text{Fe}$, but which is unlikely for $B = \text{Cr}$, may also generate small differences in anisotropy between $B = \text{Cr}$ and Fe structures that are sufficient to stabilize the

TABLE II. Irreducible representations (Γ) and basis vectors (BV) from magnetic symmetry analysis of the $P4_2/n$ CaMnBSbO_6 double double perovskites for propagation vector $k = [000]$. Moment coefficients μ_x, μ_y, μ_z are shown for the A -site Mn and B -site BV's.

Symmetry operation	Γ_1		Γ_2	Γ_3		Γ_5	Γ_6
	BV _A	BV _B	BV _B	BV _A	BV _B	BV _A	BV _A
x, y, z	00+	+++	+++	++0	+++000	00+	++0
$-x + 1/2, -y + 1/2, z$		--+	--+		++-000		
$-y, x + 1/2, z + 1/2$	00+	-++	+--	++0	000-++	00-	--0
$y + 1/2, -x, z + 1/2$		+--	-+-		000-+-		

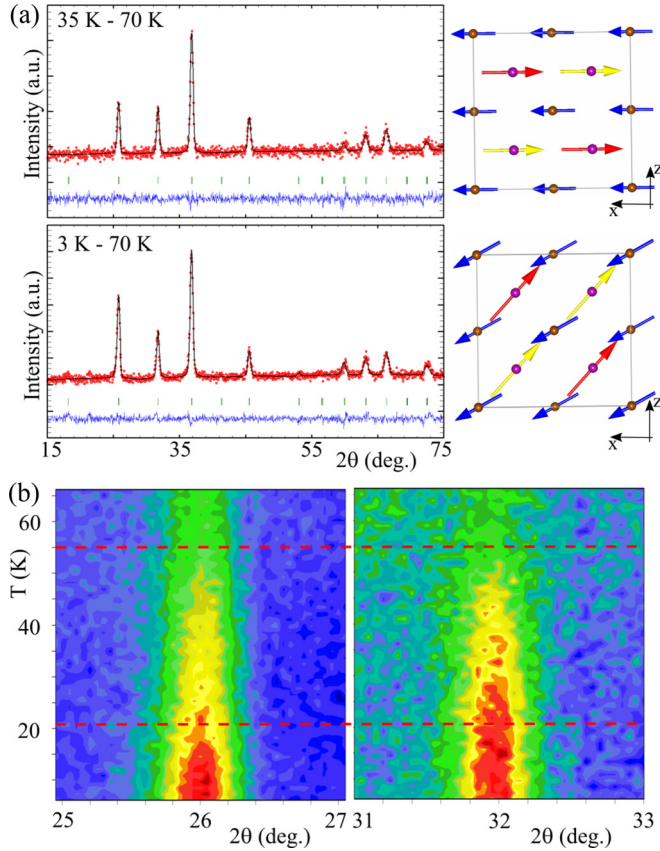


FIG. 4. (a) Rietveld fits to the CaMnFeSbO_6 NPD difference patterns 35–70 K and 3–70 K. The first three prominent magnetic peaks (observed in the range $2\theta = 25\text{--}40^\circ$) are (110)/(101), (111), and (200)/(002). The right panels show the refined magnetic structures at 35 (top) and 3 K (bottom). (b) 2D NPD short scan data showing the different thermal evolution of (110) and (111) magnetic peaks (left and right respectively). T_{C1} and T_{C2} are labeled as red dashed lines.

tilted spin ground state only in the latter material. X-ray absorption spectroscopy study of the transition metal valence states would be useful to give further insight into the different magnetic properties of these two new double double perovskites.

IV. CONCLUSIONS

The two new double double perovskites CaMnBSbO_6 ($B = \text{Cr, Fe}$) oxides can be recovered from high-pressure and high-temperature conditions. Both have tetragonal $P4_2/n$ crystal structures with cation disorder that leads to slight Mn deficiency with neutron-refined compositions $\text{CaMn}_{0.81}\text{Cr}_{1.19}\text{SbO}_6$ and $\text{CaMn}_{0.85}\text{Fe}_{1.15}\text{SbO}_6$. Both materials have collinear ferrimagnetic xy -plane spin orders with A -site Mn moments antiparallel to those at the B sites below 49 and 55 K for $B = \text{Cr}$ and Fe respectively. However, $B = \text{Fe}$ shows a second transition at 21 K where spins reorient towards the z axis. It is not clear why a reorientation transition is not also observed for $B = \text{Cr}$, but a greater degree of magnetic disorder for $B = \text{Fe}$ and possible A - B intersite charge transfer may be significant.

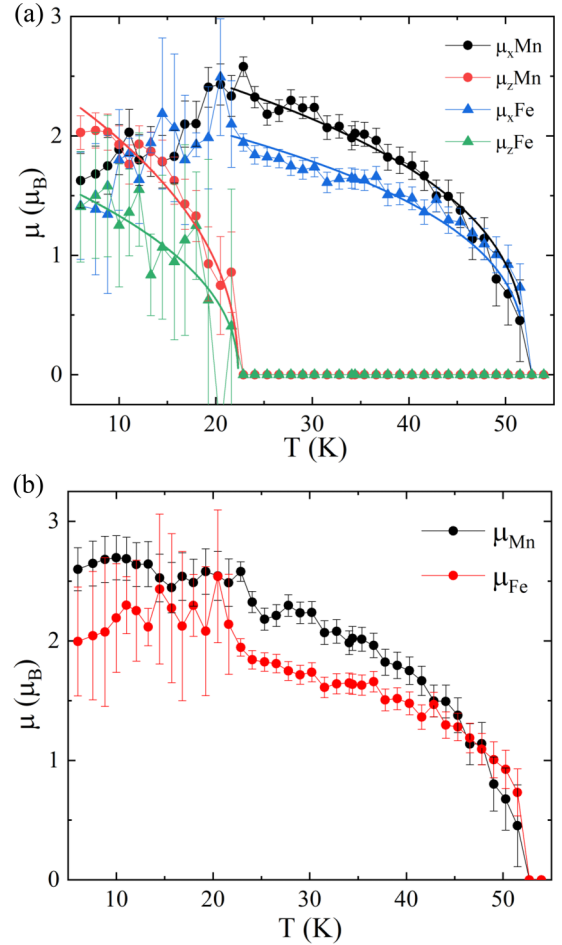


FIG. 5. Temperature variations of (a) the μ_x and μ_z components, and (b) the resultant moments μ , at Mn and Fe sites from Rietveld fits to the short NPD scans for CaMnFeSbO_6 . Critical fits shown to the μ_x and μ_z components are described in the text.

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TABLE III. Refined components of the magnetic moments in the xy plane (shown as μ_x as spin directions within the xy plane are not determined) and parallel to the z axis (μ_z) for CaMnBSbO_6 at low temperatures.

B	T (K)	Site	μ_x (μ_B)	μ_z (μ_B)	μ_{tot} (μ_B)
Cr	1.5	Mn	3.72(3)	0	3.72(3)
		B	2.82(3)	0	2.82(3)
Fe	35	Mn	3.00(4)	0	3.00(4)
		B	2.17(3)	0	2.17(3)
Fe	3	Mn	2.62(8)	2.87(5)	3.89(6)
		B	2.34(11)	1.51(16)	2.78(15)

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