**Pr$_2$FeCrO$_6$: A Type I Multiferroic**

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ABSTRACT: We synthesized double perovskite Pr$_2$FeCrO$_6$ by solid-state method. Analysis of its X-ray powder diffraction shows that the compound crystallizes in a centrosymmetric structure with space group Pbnm. Our X-ray photoelectron spectroscopy (XPS) studies show that all the cations are present in +3 oxidation state. Magnetization studies of Pr$_2$FeCrO$_6$ show that the material is paramagnetic at room temperature and undergoes a magnetic transition below $T_{CM}$ = 250 K. We observe clear magnetic hysteresis loop, for example, below 150 K. A low remnant magnetization $M_r \sim 0.05 \mu_B$/f. u., is inferred from the observed magnetic hysteresis loop. $^{57}$Fe Mössbauer study at 25 K shows a high hyperfine magnetic field of $\sim$53 T at the Fe nucleus, which corresponds to a magnetic moment of $\sim$6–7 $\mu_B$/Fe. These two results together suggest a ferrimagnetic (nearly compensated or canted) ordering of the Fe moments. Mössbauer studies close to the ferrimagnetic ordering temperature suggest interesting magnetic relaxation effects. A dielectric anomaly observed at $T_{CE}$ = 453 K signals a ferroelectric ↔ paraelectric phase transition. We observe at room temperature a clear and well-defined ferroelectric hysteresis loop, $P_r = 1.04 \mu C/cm^2$, establishing ferroelectricity in the material. From these results, we conclude that Pr$_2$FeCrO$_6$ is a type I multiferroic ($T_{CE} > T_{CM}$).

**INTRODUCTION**

Multiferroics are materials that exhibit simultaneously any two, or more than two, ferroic properties, such as ferroelectricity, ferroelasticity, ferromagnetism (antiferromagnetism), etc. Among them, the most extensively studied multiferroics are those that exhibit, below certain temperature, coexisting ferromagnetism and ferroelectricity. This is because such materials (i) are potential candidates for future technologies and (ii) often exhibit features that are quite challenging to understand. Multiferroics are of two varieties: type I multiferroics exhibit ferroelectric transition at a temperature $T_{FE}$ higher than the ferromagnetic transition temperature $T_{CM}$; that is, $T_{CE} > T_{CM}$. They have high polarization $P$ and also high $T_{CE}$. Type II multiferroics are characterized by $T_{CM} > T_{CE}$. In such materials ferroelectricity is regarded as induced magnetically, which makes them particularly interesting and challenging. Such materials usually have low polarization $P$ and low $T_{CE}$. In this work, we are concerned with disordered double perovskite multiferroics R$_2$BB'O$_6$ [where R = Y or a rare-earth element, and B and B' are transition elements]. Table 1 shows several reported double perovskite multiferroics of type I and type II.

Rajeswaran et al.\* reported multiferroic properties of Y$_2$FeCrO$_6$, $T_{CM}$ = 260 K and occurrence of ferroelectricity at and below magnetic transition temperature. Occurrence of ferroelectricity in the material was determined from the measurements of dielectric constant and spontaneous electric polarization measured using dielectric and pyroelectric measurements. Ferroelectric hysteresis loop was not reported in this work. We undertook the synthesis of a related material, namely, Pr$_2$FeCrO$_6$ which we describe here. A noteworthy aspect of Pr$_2$FeCrO$_6$ is that we observe a clear ferroelectric hysteresis loop at room temperature establishing its ferroelectric nature. It is important to note that though several double perovskites of the type RE$_2$BB'O$_6$ with multiferroic properties are known, observation of a ferroelectric hysteresis loop of this clarity has been rarely reported in these double perovskites.

**EXPERIMENTAL SECTION**

Polycrystalline Pr$_2$FeCrO$_6$ was prepared by solid-state sintering method. Stoichiometric mixture of the oxides Pr$_6$O$_{11}$, Fe$_2$O$_3$, and...
hysteresis loops were measured at 50, 150, and 300 K in a magnetic meter. Ferroelectric hysteresis loop of Pr$_2$FeCrO$_6$ was measured at temperatures between 573 and 300 K using the Agilent E4980A LCR pellets was measured in the frequency range from 100 Hz to 1 MHz at room temperature (RT) using precision P–E hysteresis loop tracer system (MarinIndia). X-ray photoemission spectroscopy (XPS) experiments were performed on Pr$_2$FeCrO$_6$ compound using Omicron Multiprobe Surface Science System, equipped with monochromatic source (XM 1000) and a hemispherical electron energy analyzer (EA 125). Throughout the experiment, photoemission spectra were studied at an average base pressure of ~2.8 × 10$^{-5}$ Torr with power of 300 W. The total energy resolution, estimated from the width of the Fermi edge, was ~0.25 eV for monochromatic Al Kα line with photon energy of 1486.70 eV. The pass energy for core-level spectra was kept at 30 eV. Ar ion sputtering was performed at 2 keV by maintaining extractor pressure of 25 mPa. $^{57}$Fe Mössbauer measurements were performed in transmission mode with $^{57}$Co radioactive source in constant acceleration mode using standard personal computer (PC)-based Mössbauer spectrometer equipped with Wissel velocity drive. Velocity calibration of the spectrometer was done with the natural iron absorber at room temperature. Low-temperature $^{57}$Fe Mössbauer measurements were performed using a Janis CCR. The spectra were analyzed with NORMOS program.

# RESULTS AND DISCUSSION

## Crystallography/Structural Aspects

Powder X-ray diffraction pattern suggests perovskite-type orthorhombic structure with unit cell parameters $a/b/c \approx \sqrt{2} a_1/\sqrt{2} a_2, a_2/a_1 = 3.9$ Å, parameter of the perovskite subcell). Systematic absence of the diffraction lines 0kl, $k+l \neq 2n$ and $h0l$, $h \neq 2n$ suggest space group $Pbnm$ (No. 62). Figure 1 shows refined powder X-ray diffraction (PXRD) pattern of Pr$_2$FeCrO$_6$. The refined lattice parameters, bond lengths, and bond angles are given in Table 2. The all the crystallographic data, occupancies, reliability factors, and the goodness of fit (GOF) are given in Table 3. The refinement of our data allows us to conclude that Fe and Cr are randomly distributed in the two B sites (B and B'). This conclusion receives support from the fact that both Fe and Cr are in the same valence state, namely, +3, as we determined from our XPS data described below. Andersen et al. have discussed the structural implications of the two B-site ions having the same valence state. One important effect is that, due to random distribution of the two B-ions, the structure becomes centrosymmetric. Our refinement analysis shows that Pr$_2$FeCrO$_6$ belongs to orthorhombic GdFeO$_3$-type centrosymmetric structure with Glazer notation $a'a''b''$ tilt system. A three-dimensional crystal structure of Pr$_2$FeCrO$_6$ is shown in Figure 2.

The small size of the A-site cation is responsible for the deviation of the structure of Pr$_2$FeCrO$_6$ from cubic to orthorhombic structure. We calculate the octahedral distortion using the formula $\Phi = (180 - \theta)/2$, where $\theta$ is the average Fe/ Cr–O–Fe/Cr bond angle. The value of $\Phi = 11.2^\circ$ indicates that the octahedra are slightly distorted from the equilibrium position.

## Valence States of Pr, Fe, Cr, and O from XPS Spectra

X-ray photoemission experiments performed at room temperature on our compound are shown in Figure 3a-e. Figure 3a

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### Table 1. Some Double Perovskite Oxides with Multiferroic Properties

<table>
<thead>
<tr>
<th>double perovskite</th>
<th>$T_{CE}$ (K)</th>
<th>$T_{CM}$ (K)</th>
<th>space group (temp)</th>
<th>structure</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Bi}_2\text{NiMnO}_6$</td>
<td>485</td>
<td>140</td>
<td>C2→P2$_1$/n (300→500 K)</td>
<td>ordered</td>
<td>4</td>
</tr>
<tr>
<td>$\text{Bi}_2\text{NiTiO}_6$</td>
<td>513</td>
<td>58</td>
<td>$Pn2_1a$ (RT)</td>
<td>ordered</td>
<td>5</td>
</tr>
<tr>
<td>$\text{Y}_2\text{FeMnO}_6$ (single crystal)</td>
<td>328</td>
<td>245, 328, 358</td>
<td>$Pnma$ (RT)</td>
<td>disordered</td>
<td>6</td>
</tr>
<tr>
<td>$\text{Y}_2\text{CrMnO}_6$ (single crystal)</td>
<td>390</td>
<td>74</td>
<td>$Pnma$ (RT)</td>
<td>disordered</td>
<td>6</td>
</tr>
<tr>
<td>$\text{Sr}_2\text{ZrMnO}_6$</td>
<td>ferroelectric loop at RT</td>
<td>53.2</td>
<td>$Pnma$ (RT)</td>
<td>disordered</td>
<td>7</td>
</tr>
<tr>
<td>$\text{Y}_2\text{FeCrO}_6$ above 260</td>
<td>260</td>
<td>$Pnma$ (350 K, 2 K)</td>
<td>disordered</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>$\text{Dy}_2\text{FeCrO}_6$</td>
<td>500</td>
<td>250</td>
<td>$Pnma$ (RT)</td>
<td>disordered</td>
<td>9</td>
</tr>
<tr>
<td>$\text{CaMnTi}_2\text{O}_6$</td>
<td>630</td>
<td>10</td>
<td>$Pmnm$</td>
<td>ordered</td>
<td>10</td>
</tr>
<tr>
<td>$\text{Lu}_2\text{MnCoO}_6$</td>
<td>35</td>
<td>43</td>
<td>$P2_1/n$ (4 K, 100 K)</td>
<td>ordered</td>
<td>11</td>
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<tr>
<td>$\text{La}_2\text{MnCrO}_6$</td>
<td>67</td>
<td>67</td>
<td>$P2_1/n$ (RT)</td>
<td>ordered</td>
<td>12</td>
</tr>
<tr>
<td>$\text{Y}_2\text{NiCrO}_6$</td>
<td>80</td>
<td>80</td>
<td>$P2_1/n$ (RT)</td>
<td>ordered</td>
<td>13</td>
</tr>
</tbody>
</table>

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### Table 2. Refined Lattice Parameters, Average Bond Length, and Bond Angle of Pr$_2$FeCrO$_6$

<table>
<thead>
<tr>
<th>Bond</th>
<th>Average Bond Length (Å)</th>
<th>Bond Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a/\text{Fe}/\text{Cr}$</td>
<td>5.4758(4)</td>
<td>162.187(2)</td>
</tr>
<tr>
<td>$b/\text{Cr}$</td>
<td>5.5094(3)</td>
<td>157.348(1)</td>
</tr>
<tr>
<td>$c/\text{Fe}/\text{Cr}$</td>
<td>7.7314(4)</td>
<td>157.348(1)</td>
</tr>
<tr>
<td>Fe/Cr–O (Å)</td>
<td>1.753(2)</td>
<td>157.348(1)</td>
</tr>
<tr>
<td>Pr–O (Å)</td>
<td>2.334(3)</td>
<td>162.187(2)</td>
</tr>
<tr>
<td>Fe/Cr–O1–Fe/Cr (deg)</td>
<td>162.187(2)</td>
<td>157.348(1)</td>
</tr>
<tr>
<td>Fe/Cr–O2–Fe/Cr (deg)</td>
<td>162.187(2)</td>
<td>157.348(1)</td>
</tr>
</tbody>
</table>

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## Figure 1. Rietveld refinement profile of Pr$_2$FeCrO$_6$ obtained from PXRD data. (X) Observed, (O) calculated, and (blue) difference, respectively. Bragg peaks are denoted by green bars.

## Figure 2. Powder X-ray diffraction pattern of Pr$_2$FeCrO$_6$. 

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## Figure 3a-e. X-ray photoemission experiments performed at room temperature on our compound.
shows survey scan spectra of Pr$_2$FeCrO$_6$. Binding energy values are in good agreement with the National Institute of Standards and Technology (NIST) database, which was used to assign the position of the peaks and the spin–orbit doublet separations.\textsuperscript{18} Pr 3d core-level spectra shown in Figure 3a comprise two well-separated spin–orbit split peaks Pr(3d$_{3/2}$) and Pr(3d$_{5/2}$) at 953.37 and 932.87 eV, respectively. At low-energy side of the Pr3d$_{3/2}$ and Pr3d$_{5/2}$ main lines, there are weak lines known as shakedown satellites and correspond to the Pr 3d$^4$4f$^6$ final states.\textsuperscript{19–21} The core-level XPS Cr2p spectra reveal spin–orbit split 2p$_{3/2}$ and 2p$_{1/2}$ lines (Figure 3c). The Cr 2p$_{3/2}$ and 2p$_{1/2}$ appear at 575.8 and 585.51 eV. This doublet separation of 9.71 eV suggests that Cr exists in $+3$ oxidation state. Figure 3d shows the core-level spectra of Fe 2p region. Spin–orbit split 2p$_{3/2}$ and 2p$_{1/2}$ appear at 710.23 and 724.05 eV, respectively, with doublet separation of 13.82 eV. This corresponds to the $+3$ oxidation state of Fe. The satellite peak appearing at 718.6 eV in the Fe XPS data is the diagnostic signature of Fe$^{3+}$. In the core-level O1s spectra (Figure 3e), the peak at 528.85 eV is the characteristic peak of O$^{2−}$ ions of the lattice oxygen, while the broad peak around 531.35 eV denotes O1s lateral structure. This lateral broad peak corresponds to the ionization of weakly adsorbed species\textsuperscript{22} and also the ionizations of oxygen ions with particular coordinates, more specifically integrated in the subsurface. This suggests the subsurface consists of oxygen ions that bear lower electron density than the “O$^{2−}$” ions. Normally, these oxide ions can be described as “O$^{−}$” species or excess oxygen.\textsuperscript{23} We calculated bond valence sum (BVS) of Fe and Cr atoms using Fe–O and Cr–O bond lengths obtained from the refined X-ray data (Table 2). The valence can be calculated as the sum of the individual bond valences, $s_i = \exp\left(\frac{r_i - r_0}{B}\right)$, where $B$ is an empirical constant, typically $r_0 = 0.37$ Å, and $r_i$ and $r_0$ are calculated and theoretical M–O bond length. $r_0$ for Fe–O and Cr–O are 1.759 and 1.724 Å, respectively. BVS calculations show the valence of Fe and Cr is close to 3, consistent with that determined from the XPS measurements.

<table>
<thead>
<tr>
<th>site</th>
<th>$x$</th>
<th>$y$</th>
<th>$z$</th>
<th>atom</th>
<th>occ</th>
<th>Beq (Å$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4c</td>
<td>0.008(1)</td>
<td>−0.0371(4)</td>
<td>0.25</td>
<td>Pr</td>
<td>1</td>
<td>0.32(4)</td>
</tr>
<tr>
<td>4b</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>Fe/Cr</td>
<td>0.5/0.5</td>
<td>0.15(2)</td>
</tr>
<tr>
<td>4c</td>
<td>−0.082(1)</td>
<td>0.512(1)</td>
<td>0.25</td>
<td>O</td>
<td>1</td>
<td>0.55(7)</td>
</tr>
<tr>
<td>8d</td>
<td>0.195(4)</td>
<td>0.244(5)</td>
<td>0.062(4)</td>
<td>O2</td>
<td>1</td>
<td>0.55(7)</td>
</tr>
</tbody>
</table>

“Space group = Pbnm (No. 62), $R_p(\%) = 3.75$, $R_{wp}(\%) = 4.29$, GOF = 1.62, Z = 2, V (Å$^3$) = 233.25 (4)."
Magnetic Properties. Magnetic measurements of Pr$_2$FeCrO$_6$ were performed using vibrating sample magnetometer (VSM). Figure 4 shows the FC and ZFC magnetic susceptibility, $\chi(T)$, from 2 to 400 K in an applied magnetic field of 0.1 T. A rapid increase in the measured magnetization $M$ is observed below 190 K. The inverse susceptibility plot (inset (a) of Figure 4) suggests a transition from paramagnetic to a magnetically ordered state below ~240 K, which is also reflected in $\chi T$ versus $T$ plot shown in the inset (b) of Figure 4.

According to the Goedenoogh—Kanamori rules with high-spin Fe$^{3+}$ ($t_2g$ $e_g^3$) and Cr$^{3+}$ ($t_2g$ $e_g^3$) the 180° superexchange interaction between one half-filled $d$ orbital and other empty $d$ orbital through an anion results in ferromagnetic interaction. These rules state that due to greater cation—anion interaction, the interaction between $e_g$ orbitals will dominate over the interaction between $t_{2g}$ orbitals. As pointed out above, Fe$^{3+}$ and Cr$^{3+}$ are disordered at B sites (B and B'). A long-range order among Fe$^{3+}$ and Cr$^{3+}$ sites, as implied by the sequence Fe$^{3+}$O−Cr$^{3+}$O−Fe$^{3+}$O−Cr$^{3+}$O−Fe$^{3+}$ is not possible. In the absence of long-range order, species such as Fe$^{3+}$O−Fe$^{3+}$ ($e_g^2$O−$e_g^1$), Fe$^{3+}$O−Cr$^{3+}$ ($e_g^3$O−$e_g^0$), Cr$^{3+}$O−Cr$^{3+}$ ($e_g^2$O−$e_g^1$) would exist in the material. Despite this disorder among Fe$^{3+}$ and Cr$^{3+}$ ions the material exhibits a ferrimagnetic or weakly ferromagnetic transition as revealed by our observation of a magnetic hysteresis loop with rather low remnant magnetization, as shown in Figure 5. The observed ferrimagnetism could be G-type antiferromagnetism (AFM; a small cation to allow for weak ferromagnetism) below transition temperature. The Curie–Weiss law [$\chi = C/(T - \theta_B)$] was used to fit the susceptibility in paramagnetic region from 400 to 244 K. The negative extrapolated temperature $\theta_B$ ($\sim$73 K) is suggestive of an antiferromagnetic ordering, which is consistent with the nearly compensated magnetic structure (low magnetic moment), as we pointed out above. The paramagnetic moment calculated from our susceptibility data is 8.3 $\mu_B$ per formula unit. This may be compared with the calculated value 8.6 $\mu_B$ using the individual ionic moments as $\mu_{Fe^{3+}} = 3.5$ $\mu_B$, $\mu_{Cr^{3+}} = 5.92$ $\mu_B$, and $\mu_{O^{2-}} = 3.87$ $\mu_B$. Field-dependent magnetization measured at 5 T field and at three different temperatures 300, 150, and 50 K is shown in Figure 5. Magnetic hysteresis loop was observed at 150 and 50 K, which indicates the overall ferromagnetic nature of the compound.

Mössbauer Spectroscopic Studies. $^{57}$Fe Mössbauer spectra of Pr$_2$FeCrO$_6$ at several temperatures are shown in Figure 6a. Our analysis of the room-temperature spectrum, which apparently is a single line, suggests that the spectrum is actually a nonresolved doublet with quadruple splitting of $\sim$0.21 ± 0.04 mm/s and no magnetic splitting thereby indicating that the material has a noncubic structure and that the compound is paramagnetic at room temperature. The observed isomer shift of 0.37 ± 0.02 mm/s indicates the presence of Fe$^{3+}$, which is consistent with the results of our other measurements. The spectrum at 25 K is fit to a sextet, and the obtained center shift and internal hyperfine field values are 0.48 ± 0.01 mm/s and 53.0 ± 0.1 T respectively. Similar values corresponding to Fe$^{3+}$ have been observed in other double perovskites such as Sr$_2$FeMoO$_6$. From this hyperfine field we estimate the magnetic moment $\sim$6−7 $\mu_B$ on Fe$^{3+}$ ion in this material. This magnetic moment was calculated on the basis of an empirical relationship between the hyperfine field on Fe nucleus and the magnetic moment, and by its nature this relationship is only suggested but not accurate. However, this is not too far from the moment of free Fe$^{3+}$ in the high-spin state. Data above 150 K are fit with a distribution of hyperfine fields as shown in Figure 6. From the low-temperature Mössbauer data, internal hyperfine field is estimated and is plotted as a function of temperature as shown in Figure 6b.

The spectra below 250 K show remarkable temperature-dependent phenomena occurring in the material. There is magnetic hyperfine field at the Fe nucleus appearing at $T \leq 250$ K. In a narrow range of temperature, 260 K < $T < 220$ K, interesting relaxation effects associated with Fe moment dynamic fluctuations are observed. Well split, but with dynamically induced line-broadening, six-finger pattern of Fe-site spectrum is observed at 200 K and down to 100 K. Hyperfine field (HF) split sharp Mössbauer spectra are observed at and below ~100 K. At 25 K, the HF at the Fe nucleus is ~53 T.

Ferroelectricity and Multiferroicity. We investigated the dielectric properties of sintered pellets from 300 to 573 K applying alternating-current (ac) field from 100 Hz to 2 MHz frequency range. The variation of dielectric constant with temperature at different frequencies is shown in Figure 7. Anomaly observed at 453 K indicates a ferroelectric to paraelectric phase transition. Ferroelectricity in our sample is clearly observed in our electric polarization measurements of Pr$_2$FeCrO$_6$ in an applied electric field. Figure 8 shows the...
ferroelectric hysteresis loop of Pr$_2$FeCrO$_6$ at three temperatures 300, 310, and 320 K. The loops are nearly symmetric and well-formed. The values of the saturation polarization $P_S$ and coercivity $E_c$, as obtained from the observed loops, are 1.04 $\mu$C/cm$^2$ with 4.77 kV/cm, respectively. The remnant polarization as we note from Figure 8 is $\sim$0.6 $\mu$C/cm$^2$, which is much smaller than in CaMnTi$_2$O$_6$ $^{10}$ (3.5 $\mu$C/cm$^2$). The hysteresis loop could not be observed at higher temperatures due to increase in the leakage current. To the best of our knowledge very few double perovskite materials have been reported exhibiting ferroelectric hysteresis loop. One such example is CaMnTi$_2$O$_6$, as we noted above. In our case, observation of hysteresis loop becomes particularly noteworthy, as $P_S$ in our case is very small; it is several times smaller than in CaMnTi$_2$O$_6$. We must also point out that the structure of the compound CaMnTi$_2$O$_6$ from X-ray diffraction pattern was determined to be centrosymmetric, space group $P4_{2}/nmc$, despite its $P_S$ being so high as compared with $P_S$ in our material. Occurrence of ferroelectricity in most double perovskite ferroelectrics was inferred from the measurements of pyroelectric and oscillation current, $^{12,13}$ as hysteresis loop was not observed because of high leakage current.

We must point out that the space group $Pbnm$ of the structure of our material Pr$_2$FeCrO$_6$, as derived from X-ray data, is centrosymmetric. Such a space group is inconsistent with the ferroelectric nature of the compound. We believe this apparent inconsistency may be resolved considering that Fe and Cr ions are randomly distributed over the two sites B and B’. The bulk of compound, due to this disorder, is rendered centrosymmetric, $^{33}$ as we see in our X-ray diffraction. Dy$_2$FeCrO$_6$ $^{9}$ is another such example. In their work, the authors $^{9}$ emphasize that the material is centrosymmetric as

Figure 6. (a) $^{57}$Fe Mössbauer spectra of Pr$_2$FeCrO$_6$ at several temperatures. The spectrum at 250 K, compared with the spectra at 290 and 200 K, suggests the presence of magnetic relaxation effects. Detailed study of these effects would be studied in our further studies. (b) Average hyperfine field as observed from fits of Mössbauer spectra.

Figure 7. Temperature-dependent dielectric constant of Pr$_2$FeCrO$_6$ measured at different frequencies.

Figure 8. Ferroelectric hysteresis loop of Pr$_2$FeCrO$_6$ at three different temperatures 300, 310, and 320 K under the field of 12 kV cm$^{-1}$. 

inferred from their X-ray diffraction. However, they observe ferroelectricity at room temperature. However, it is entirely conceivable that there are micro-regions in the material where the two sites are locally ordered giving rise to local non-centrosymmetric structure. Such embedded regions in the bulk of the material would be ferroelectric. As relative fraction of such regions is small, we see no diffraction lines corresponding to this ordered structure. This explains also the weak $P_s$ in our case. In support of this conjecture, we point out that recent observation of local non-centrosymmetry has been reported in weakly biferroic $\text{YCrO}_3$.34 We believe such a scenario exists, for example, in $\text{Y}_2\text{FeCrO}_6$ and $\text{Dy}_2\text{FeCrO}_6$. The other possibility of explaining low $P_s$ is that $P_s$ arises due to ionic displacements just as it does in well-known displacive ferroelectrics. But these displacements have to be small, consistent with low value of $P_s$. Though the symmetry is broken due to these ionic displacements (the material becomes non-centrosymmetric), the displacements are small. We think our material is an ideal material to investigate all these subtle issues. Our work is in progress.

**CONCLUSION**

A disordered double perovskite material Pr$_2$FeCrO$_6$ has been synthesized as a single phase by solid-state method at 1100 °C. The PXRD refined data suggests orthorhombic $Pbnm$ structure. XPS data show that all the cations have $+3$ oxidation state. Magnetization studies of Pr$_2$FeCrO$_6$ show that material is paramagnetic at room temperature and undergoes a magnetic transition below 250 K. We observe clear magnetic hysteresis loop, for example, below 150 K. A low remnant magnetization $M_r\sim0.05\ \mu_B/\text{f.u.}$ is inferred from the observed magnetic hysteresis loop. $^{57}\text{Fe}$ Mössbauer study at 25 K shows a high hyperfine magnetic field of $\sim53$ T at the Fe nucleus that corresponds to a magnetic moment of $\sim6-7\ \mu_B$. Interesting magnetic relaxation effects are observed close to the ferrimagnetic ordering temperature. We investigated the ferroelectric nature of the compound. The dielectric anomaly at 453 K and formation of hysteresis loop suggests that the compound is ferroelectric above room temperature. The $P_s$ of the compound $1.04\ \mu C/cm^2$ is small in comparison to the other reported ferroelectric compounds. We feel that the small value of saturation polarization is due to the local non-centrosymmetric structure of the compound. Pr$_2$FeCrO$_6$ has interesting ferroelectric and ferrimagnetic properties and is a type I multiferroic material.

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The authors declare no competing financial interest.

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**REFERENCES**


(28) Antoshina, L. G.; Goryaga, A. N.; Kukudzhanova, E. N. Effect of \( \text{Cr}^{3+} \) ions on the magnetic moment of ferrites of the system \( \text{CuFe}_2\text{O}_4-x\text{Cr}_x\text{O}_4 \). *Phys. Solid State* 1998, 40, 99–108.


(33) Turp, S. A.; Hargreaves, J.; Baek, J.; Shiv Halasyamani, P.; Hayward, M. A. Noncentrosymmetric Cation Order in the Cubic Perovskite \( \text{Ba}_4\text{CaFe}_6\text{O}_{14.5} \). *Chem. Mater.* 2010, 22, 5580–5587.