






PAPER

[View Article Online](#)
[View Journal](#) | [View Issue](#)Cite this: *Dalton Trans.*, 2022, **51**,
15361Anionic ordering in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ revisited by nuclear
magnetic resonance and density functional
theory†‡Kengo Oka, *§^a Tom Ichibha, *§^b Daichi Kato, ^c Yasuto Noda,^d
Yusuke Tominaga,^d Kosei Yamada,^a Mitsunobu Iwasaki,^a Naoki Noma,^e
Kenta Hongo, ^f Ryo Maezono ^g and Fernando A. Reboredo^b

A combination of ^{19}F magic angle spinning (MAS) nuclear magnetic resonance (NMR) and density functional theory (DFT) were used to study the ordering of F atoms in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$. This analysis revealed that F atoms predominantly occupy two of the six available inequivalent sites in a ratio of 73 : 27. DFT-based calculations explained the preference of F occupation on these sites and quantitatively reproduced the experimental occupation ratio, independent of the choice of functional. We concluded that the Pb atom's $6s^2$ lone pair may play a role (~ 0.1 eV per f.u.) in determining the majority and minority F occupation sites with partial density of states and crystal orbital Hamiltonian population analyses applied to the DFT wave functions.

Received 17th March 2022,

Accepted 26th July 2022

DOI: 10.1039/d2dt00839d

rsc.li/dalton

1 Introduction

Understanding the mechanisms that produce ionic ordering in materials may lead to control of the self-assembly of ordered super lattices on an underlying crystal structure. Because ordered and disordered structures have remarkably

different electronic and transport properties, controlling ordering is a key step in material design. For example, the properties of mixed-anion compounds strongly depend on the degree of order or disorder of the anions.^{1,2} Anionic ordering can cause heteroleptic coordinations or low-dimensional structures, which in turn modify electronic properties.^{1,2} This intriguing possibility to modify a material has attracted significant attention.^{3–6} Some ABX_3 perovskites are typical examples. SrTaO_2N and BaTaO_2N have a high dielectric constant because of their O/N anionic ordering.^{7–9} In addition, an oxyhydride SrVO_2H shows two-dimensional electron conduction and compression anisotropy because of the O/H anionic ordering.¹⁰

In complex composite materials, multiple anions and cations are heteroleptically coordinated, and their concentrations typically obey valence charge neutrality conditions. When differences in ionic radii, electronegativity, or polarizability are large, some materials tend to exhibit ionic ordering.^{11,12} However, although O^{2-} and F^- are neighboring anions in the periodic table, the oxyfluorides nevertheless exhibit anionic ordering, depending on the structure. Whereas simple cubic perovskites (SrFeO_2F ,¹³ BaFeO_2F ,¹⁴ PbScO_2F ,¹⁵ BaScO_2F ,¹⁶ AgFeO_2F ,¹⁷ BaInO_2F ,¹⁸ and AgTiO_2F ¹⁹) adopt disordered configurations, a variety of Ruddlesden–Popper-type layered perovskites ($\text{Sr}_2\text{CuO}_2\text{F}_2$,²⁰ $\text{Sr}_2\text{FeO}_3\text{F}$,^{21,22} $\text{Ba}_2\text{InO}_3\text{F}$,²³ $\text{Ba}_2\text{ScO}_3\text{F}$,²⁴ $\text{Sr}_2\text{MnO}_3\text{F}$,²⁵ $\text{Sr}_3\text{Fe}_2\text{O}_{5-x}\text{F}_y$ ^{21,26}) exhibit ordered configurations of F^- .²⁷ For an ordered structure to be formed, migration energy barriers must be small enough to allow the minimum free energy configuration to be achieved *via* practi-

^aDepartment of Applied Chemistry, Faculty of Science and Engineering, Kindai University, Higashiosaka, Osaka 577-8502, Japan. E-mail: koka@apch.kindai.ac.jp^bMaterials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA. E-mail: ichibha@icloud.com^cDepartment of Energy and Hydrocarbon Chemistry, Graduate School of Engineering, Kyoto University, Kyoto 615-8510, Japan^dDivision of Chemistry, Graduate School of Science, Kyoto University, 606-8502 Kyoto, Japan^eJoint Research Center, Kindai University, Higashiosaka, Osaka 577-8502, Japan^fResearch Center for Advanced Computing Infrastructure, JAIST, Asahidai 1-1, Nomi, Ishikawa 923-1292, Japan^gSchool of Information Science, JAIST, Asahidai 1-1, Nomi, Ishikawa 923-1292, Japan†This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<https://energy.gov/downloads/doe-public-access-plan>).‡Electronic supplementary information (ESI) available. CCDC 2159898, 2159899 and 2191023. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d2dt00839d>

§These two authors contributed equally.

cal annealing temperatures and times. The lowest energy structure frequently can be found by considering Pauling's second rule,²⁸ which explains that an ionic structure will be stable when the sum of the strength of the electrostatic bonds around an ion are equal to its charge. Thus, according to Pauling's second rule, F^- should prefer a more open site compared with O^{2-} , leading to O/F anionic ordering. Some non-layered oxyfluorides with or akin to perovskite structure showing a complete or partial anionic ordering have been reported, such as $Pb_2Ti_2O_{5.4}F_{1.2}$,²⁹ Pb_2OF_2 ,³⁰ and $Pb_2Ti_4O_9F_2$.³¹ The anionic ordering of some nonlayered oxyfluorides is considered to be due to the Jahn–Teller distortion by the $6s^2$ lone pair.^{29,31}

Among the nonlayered oxyfluorides with anionic ordering, $Pb_2Ti_4O_9F_2$ is especially attractive to study because this material uniquely has an isostructural oxide $Bi_2Ti_4O_{11}$.^{31,32} Both Pb^{2+} and Bi^{3+} have the same electronic configuration and $6s^2$ lone pairs. $Bi_2Ti_4O_{11}$ undergoes antiferroelectric-paraelectric transitions from $C2/c$ to $C2/m$, whereas $Pb_2Ti_4O_9F_2$ does not.^{31,32} The high-temperature paraelectric phase of $Bi_2Ti_4O_{11}$ ($C2/m$) adopts the same space group symmetry as $Pb_2Ti_4O_9F_2$.³² Because the $Bi_2Ti_4O_{11}$ -type structure is significantly low symmetric, an anionic ordering can exist in $Pb_2Ti_4O_9F_2$. Structural analyses based on the synchrotron X-ray diffraction (SXRD) patterns revealed the presence of anionic ordering.³¹ However, this conclusion is debatable because heavier Pb atoms in the system could hamper the identification of F occupation sites.

In this work, the anionic ordering in $Pb_2Ti_4O_9F_2$ was reexamined *via* a combination of ^{19}F magic angle spinning (MAS) nuclear magnetic resonance (NMR) experiments and density functional theory (DFT) simulations. The ^{19}F MAS NMR analysis revealed that F atoms randomly occupy two of the six sites in a ratio of 73 : 27, overturning the previous conclusion that F atoms selectively occupy a single site.³¹ DFT calculations identified the majority and minority F occupation sites and quantitatively reproduced the experimental occupation ratio, independent of the choice of functional. Partial density of states (PDOS) and crystal orbital Hamiltonian population (COHP) analyses were performed on the DFT results, showing that the $6s^2$ lone pairs may play a role (~ 0.1 eV per f.u.) in determining the majority and minority F occupation sites. On the other hand, DFT calculations revealed that the low-symmetric anionic coordinates around the cations may barely be due to the steric effects of $6s^2$ lone pairs. This result goes against the current discussion in this class of materials and implies that the influence of $6s^2$ lone pairs on the structural distortion might be similarly not significant in some of the other Pb-based oxyfluorides such as $Pb_2Ti_2O_{5.4}F_{1.2}$ ²⁹ and Pb_2OF_2 .³⁰

2 Experimental details

The powder samples of $Pb_2Ti_4O_9F_2$ and $Bi_2Ti_4O_{11}$ were prepared by solid-state reaction, as previously reported.^{31,32} The

$Pb_2Ti_4O_9F_2$ was synthesized from a mixture of PbO (99.9%, Rare Metallic Co.), PbO_2 (99.9%, Rare Metallic Co.), PbF_2 (99.9%, Rare Metallic Co.), and TiO_2 (rutile, 99.9%, Rare Metallic Co.) powders that were weighed to be 10 mol% F-rich to compensate for the loss of F during the reaction.³³ The pelletized mixture was sealed in an evacuated Pyrex tube and treated at 823 K for 12 h in an electric furnace, followed by natural cooling to room temperature. The $Bi_2Ti_4O_{11}$ was synthesized from a stoichiometric mixture of Bi_2O_3 (99.9%, Rare Metallic Co.) and TiO_2 (99.9%, Rare Metallic Co.) powders. The pelletized mixture was treated at 1273 K for 12 h in air in an electric furnace, followed by natural cooling to room temperature.

Production of a single phase for both $Pb_2Ti_4O_9F_2$ and $Bi_2Ti_4O_{11}$ samples were confirmed *via* SXRD. SXRD patterns were collected with a large Debye-Scherrer camera installed at beamline BL02B2 of the SPring-8 synchrotron radiation facility using a glass capillary and a solid-state detector.³⁴ The crystallographic parameters were refined by the Rietveld method using the RIETAN-FP program.³⁵ The electron density distributions were estimated by the maximum entropy method (MEM) using the Dysnomia program.³⁶

Solid-state NMR experiments were conducted on a home-made spectrometer with a 4 mm T3 probe (Varian) in a magnetic field of 4.7 T. All ^{19}F NMR transients under MAS were accumulated using a background suppression method. The radio frequency field strength was 100 kHz, corresponding to 2.5 μs of $\pi/2$ pulse length. The longitudinal relaxation time (T_1) was obtained by analyzing a build-up curve measured with a saturation recovery method. Rotational resonance experiments, which allow for solving whether the chemical-shift filter was set to half of the inverse of the difference between two signals and the MAS rate, was set to the inverse of the difference between two signals in rotational resonance experiments (further details given in ESI†).

3 Calculation details

The DFT calculations were performed with Quantum Espresso.³⁷ Perdew–Burke–Ernzerhof (PBE),³⁸ Becke–Lee–Yang–Parr (BLYP),^{39,40} and Perdew–Wang 1991 (PW91)^{41,42} semi-local exchange–correlation functionals were employed. The valence orbitals were expanded with plane waves. The cutoff energy was 100 Ry, and the k -point mesh was $7 \times 7 \times 5$ for a unit cell. With this choice of parameters, the energy difference between the first and second most stable anionic ordering patterns of $Pb_2Ti_4O_9F_2$ converged below 2 meV per f.u. These two ordering patterns are denoted as F-in-site6 and F-in-site5 in section 4.1. The core orbitals were described by the projector augmented wave (PAW) method.⁴³ PAW pseudopotentials were taken from the pslibrary.⁴⁴ Comparing the results of PAW and ultrasoft pseudopotentials in the pslibrary⁴⁴ revealed that the relative total energies among the different anionic orderings are identical within 1 meV per f.u.



Therefore, the errors from pseudopotential approximation would be negligible for this system. Ultrasoft pseudopotentials were used to calculate the electrostatic energies because PAW pseudopotentials cannot separately provide the electrostatic energies because the one-center term includes both electrostatic and exchange–correlation energies.⁴⁵ The PDOS of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ was obtained with the PBE functional. The LOBSTER code⁴⁶ was used to perform the COHP analyses based on the PBE-DFT results with the pbeVasFit2015 basis set.^{47,48} Every DFT calculation was performed for the energetically optimized structure.

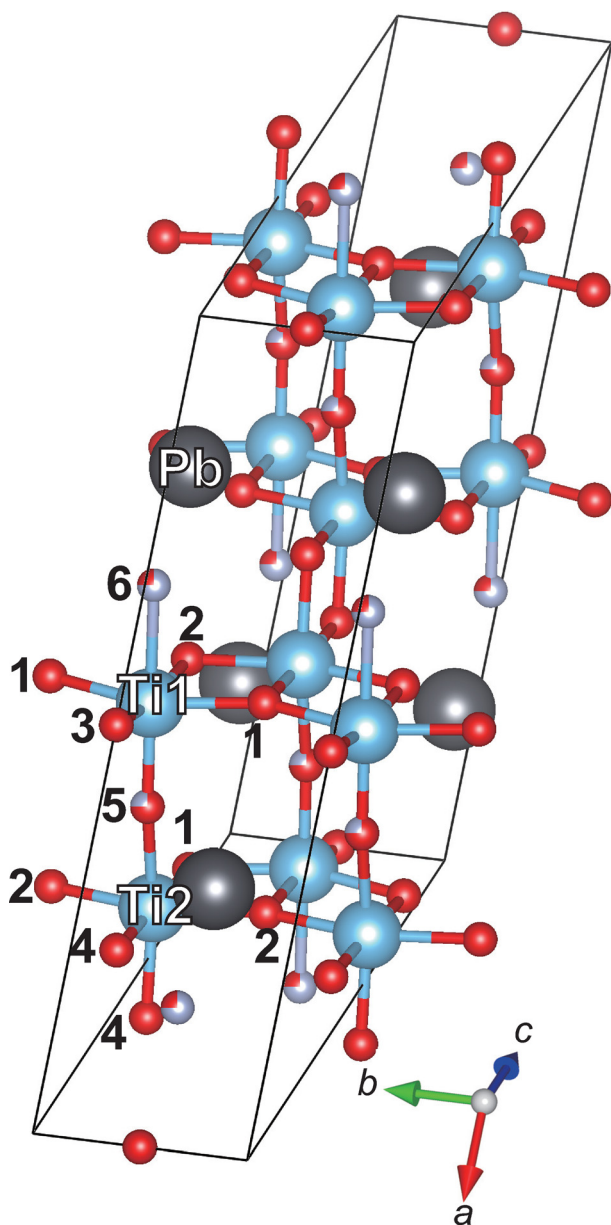


Fig. 1 The crystal structure of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ at 300 K. The numbers indicate the numbers of anion sites.

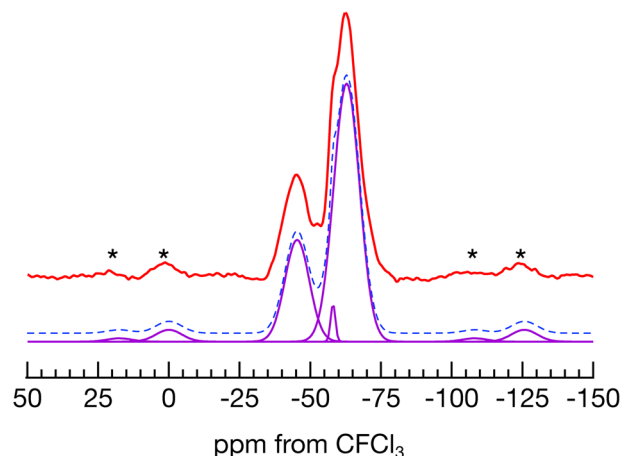


Fig. 2 A ^{19}F MAS NMR spectrum of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ (top) and peak fitting result (bottom). The asterisks indicate spinning sidebands.

Table 1 Comparisons of the energy differences (eV per f.u.) between alternative anionic ordering patterns in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$. All energies are differences with the energy of F-in-site6. The percentages indicate the ratios of the corresponding Boltzmann factors at the synthesis temperature, 823 K. F-in-site3 does not indicate an anionic ordering pattern different from the others, as described in the main text

	ΔE (PBE)	ΔE (BLYP)	ΔE (PW91)
F-in-site1	1.019 (0.0%)	0.965 (0.0%)	1.018 (0.0%)
F-in-site2	0.935 (0.0%)	0.889 (0.0%)	0.937 (0.0%)
F-in-site3	0.513 (0.1%)	0.514 (0.1%)	0.543 (0.0%)
F-in-site4	0.321 (0.8%)	0.308 (0.9%)	0.322 (0.7%)
F-in-site5	0.061 (29.5%)	0.066 (28.0%)	0.058 (30.3%)
F-in-site6	0.000 (69.7%)	0.000 (71.1%)	0.000 (69.0%)

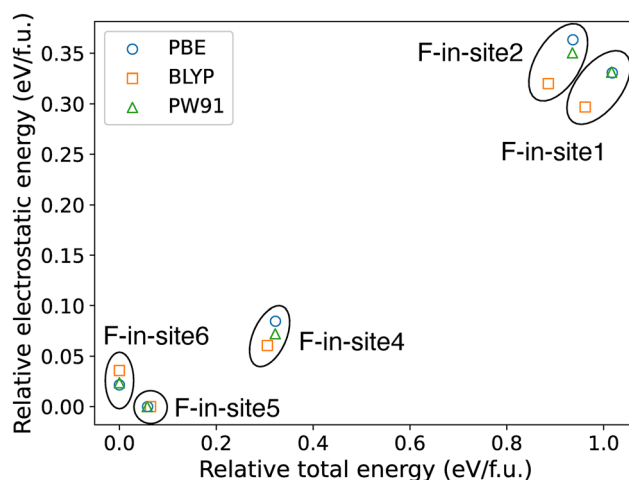


Fig. 3 Comparison of electrostatic energies and total energies calculated by DFT, using PBE (blue circles), BLYP (orange squares), and PW91 (green triangles) functionals. The minimum electrostatic energy (*i.e.*, F-in-site5) and total energy (*i.e.*, F-in-site6) are set to be zero, and the others are relative to this for every functional.



4 Results and discussion

4.1 Determination of anionic configurations

As shown in Fig. 1, $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ has six different anion sites, which are denoted by site 1–6. Previous structural analysis based on SXRD patterns has indicated that F atoms selectively occupy site 6, which is the closest site to the Pb atom.³¹ Here, that earlier conclusion is reexamined using NMR experiments and DFT simulations.

A ^{19}F MAS NMR spectrum of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ is shown together with a peak fitting result in Fig. 2. By fitting the spectrum with three Gaussians, the peak positions were obtained as -45 ppm, -58 ppm, and -63 ppm, with an area ratio of 26.1:1.8:72.1. The peak positions correspond to the ^{19}F atoms in different distinct sites, and the area ratio indicates their occupancy ratio. Through-space correlation NMR experiments were conducted to confirm whether the ^{19}F atoms

showing in the two main peaks exist in the same crystal phase. When the MAS rate was matched to the resonant frequency difference of the two main peaks, both peak intensities varied periodically with mixing time. However, when the MAS rate was faster than the resonant frequency difference, neither peak intensity changed (details in ESI†). This means that the dipole interaction that disappeared because of MAS was reintroduced by rotational resonance, and the magnetization was exchanged during the mixing time. Thus, the F sites showing the two main signals are nearby in the same crystalline phase, $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$.

The position of the F occupation sites corresponding to the two main peaks in the ^{19}F MAS NMR experiment must be determined using another method. Therefore, the energies of different F occupation patterns were evaluated with DFT to find the majority and minority F occupation sites corresponding to the two main peaks. In reality, numerous F occu-

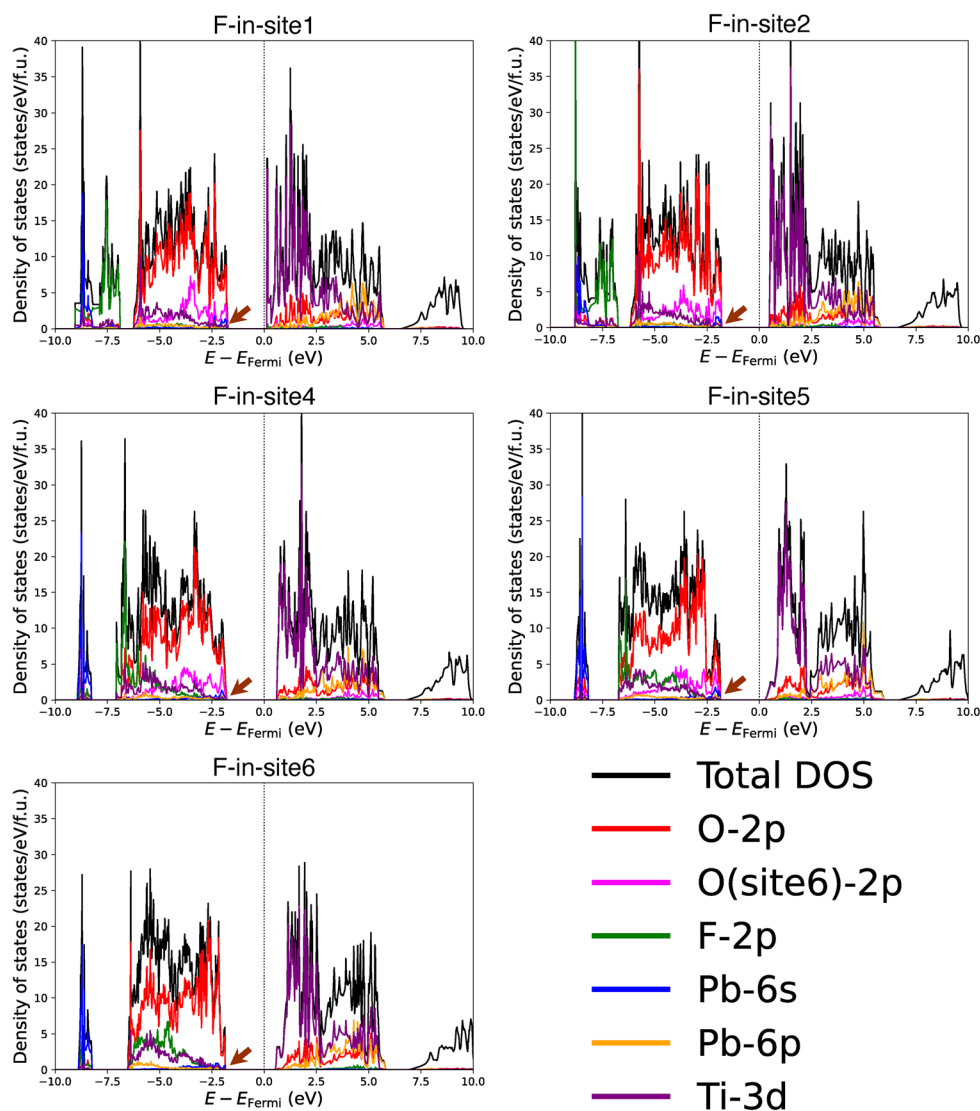


Fig. 4 PDOS of different F occupation patterns obtained by DFT. The arrows indicate the peaks accompanied by the antibonding hybrid orbitals explained by the lone-pair model. For the F-in-site6 case, the O(site6)-2p distribution is not shown because site 6 is occupied by F atoms.



pation patterns are possible, and we cannot study all of them. Therefore, targets were restricted to be the cases in which F atoms selectively occupy each of the sites, and the F atom's stability in each site was evaluated. Table 1 lists the relative total energies given by PBE,³⁸ BLYP,^{39,40} and PW91^{41,42} functionals. In the table, for example, F-in-site2 indicates the case in which F atoms selectively occupy site 2. The F stability at site 3 was evaluated as $E(\text{F-in-site3}) \equiv 2E(\text{one F atom in site 3 and the other in site 6 in the unit cell}) - E(\text{F-in-site6})$ because the multiplicity of site 3 is one (multiplicity of the other sites is two). The three functionals qualitatively and quantitatively agree with each other. F-in-site6 and F-in-site5 give the first and second lowest energies, so the majority and minority F occupation sites are sites 6 and 5, respectively. The experimental third tiny peak at -58 ppm corresponds to the F occupancy in site 4. The percentages in the parentheses in Table 1 indicate the ratios of Boltzmann factors of the relative energies under the synthesis temperature, 823 K. These percentages correspond to the F occupation ratio of the anion sites. The ratio between the percentages of F-in-site6 and F-in-site5, approximately 70 : 30, closely agrees with that between the experimental F occupation ratios of the majority and minority sites, 73 : 27.

4.2 Reason why sites 5 and 6 have a preference for F atoms

To understand the origin of the F-in-site6 and F-in-site5 stabilization, PBE,³⁸ BLYP,^{39,40} and PW91^{41,42} functionals were used to compare the electrostatic energies with the total energies, as shown in Fig. 3. The results of the three functionals are qualitatively consistent with each other. The total energies in Fig. 3

are identical to those listed in Table 1. The total energies are roughly proportional to the electrostatic energies, consistent with a previous systematic study on NdNiO_2F by simulations.⁴⁹ However, F-in-site6, which had the lowest total energy, is an exception to Pauling's second rule²⁸ because the lowest electrostatic energy was predicted for the F-in-site5.

The reason of the small deviation (~ 0.1 eV per f.u.) from Pauling's second rule²⁸ is unclear. However, the steric effects introduced by the $6s^2$ lone pairs may explain this deviation. Fig. 4 shows the PDOS of each F ordering pattern in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ given by the PBE functional. A peak of Pb-6s (indicated by an arrow) hybridized with O-2p exists at the valence band maximum (VBM). This peak is considered to be a signal of the orbital hybridization described by the revised lone-pair (RLP) model.⁵⁰ This model proposes that the antibonding hybridized orbital of Pb-6s and O-2p_z is further stabilized by hybridizing with the Pb-6p orbital. This antibonding orbital distributes opposite to the O⁵⁰ and interrupts bonding with the other anions. The PDOS figures show that F-in-site6 has the smallest Pb-6s peak (*i.e.*, the weakest RLP hybridization), presumably owing to the absence of O6 (*i.e.*, an O ion in site 6) that is the closest to Pb and has the largest 2p density of states (DOS) at the VBM. Furthermore, the magnitudes of the hybridization between Pb-6s and O/F6-2p were evaluated for F-in-site5 and F-in-site6 in terms of integrated COHP (ICOHP) by the COHP analysis applied to the PBE-DFT results. Here, ICOHP indicates how much the hybridization contributes to the stabilization by the binding. The ICOHPs of Pb-O6 in F-in-site5 and Pb-F6 in F-in-site6 are -2.81 and -0.90 eV, so the contribution of the $6s^2$ lone pair is certainly smaller when F

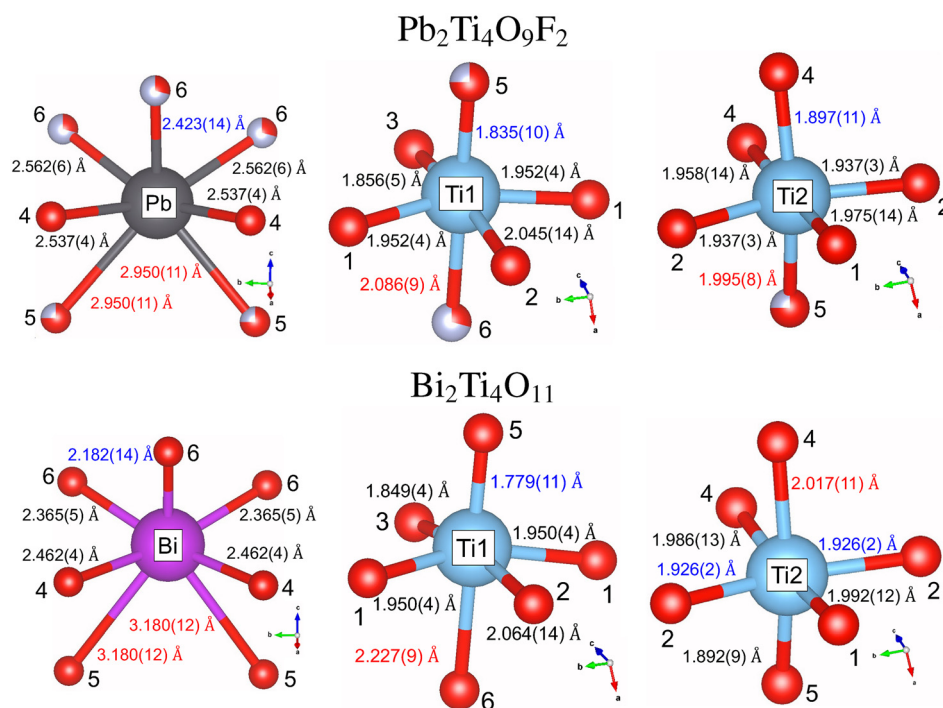


Fig. 5 Experimental geometries of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ and $\text{Bi}_2\text{Ti}_4\text{O}_{11}$ obtained via Rietveld refinement of SXRD patterns. The smallest and largest interatomic distances are shown with blue and red colors, respectively.



Table 2 Parameters of the experimental structure and DFT structures (F-in-site5 and F-in-site6) obtained for $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$. The values for the DFT structures are given as the mean values of the three functionals. The errors indicate the unbiased deviations of the means. The second rows for the F-in-site6 and F-in-site5 indicate the differences from experimental values in percentages

		<i>a</i>	<i>b</i>	<i>c</i>	β (°)	Pb-O/F4	Pb-O/F5	Pb-O/F6 ^{shorter}	Pb-O/F6 ^{longer}
Expt.	Å	14.63	3.83	10.75	135.58	2.56	2.95	2.42	2.56
F-in-site6	Å	15.07(8)	3.84(1)	10.54(7)	133.44(6)	2.54(1)	2.93(2)	2.44(1)	2.58(1)
	%	+3.0(6)	+0.3(3)	−2.0(7)	−1.6(1)	−0.1(3)	−0.8(5)	+1.0(2)	+0.9(2)
F-in-site5	Å	14.83(7)	3.84(1)	10.60(6)	132.30(2)	2.58(1)	3.03(1)	2.37(1)	2.58(2)
	%	+1.4(5)	+0.2(3)	−1.4(6)	−2.4(1)	+1.6(3)	+2.7(4)	−2.0(4)	+0.9(6)

atoms occupy site 6. This explanation for the F-in-site6 stabilization is an exception to Pauling's second rule.²⁸

4.3 Comparison between $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ and $\text{Bi}_2\text{Ti}_4\text{O}_{11}$

Fig. 5 compares the experimental structures of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ and $\text{Bi}_2\text{Ti}_4\text{O}_{11}$, which were obtained by the Rietveld analysis of SXRD patterns. The SXRD patterns are provided in the ESI.† Comparing the isostructural $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ and $\text{Bi}_2\text{Ti}_4\text{O}_{11}$, the anionic configurations around the cations are more symmetric in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ than in $\text{Bi}_2\text{Ti}_4\text{O}_{11}$. For example, the difference of the smallest (blue) and largest (red) interatomic distances are smaller in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ than in $\text{Bi}_2\text{Ti}_4\text{O}_{11}$. It is worth noting that this trend is the exact opposite of some Ruddlesden–Popper-type layered perovskites. The (B site metal)– O_6 octahedra in layered perovskite oxides are often distorted by the Jahn–Teller effect.^{21,51} The F atoms selectively occupy the apical sites and lead to significantly longer (B site metal)–F^{apical} distance than (B site metal)–O^{apical} and O^{equatorial} distances.^{20–25} However, the oxyfluoride $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ is less distorted than the isostructural oxide $\text{Bi}_2\text{Ti}_4\text{O}_{11}$, as shown in Fig. 5.

Table 2 compares the experimental structure and theoretical F-in-site6 and F-in-site5 structures of $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$. The theoretical values are given as the mean values of the three functionals. The errors indicate the unbiased deviations of the means. The F-in-site5 is slightly less symmetric than F-in-site6, but their differences are not significant, which indicates that the low-symmetric anionic configurations around the cations in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ are barely due to the steric effects of $6s^2$ lone pairs: the structure is naively low-symmetric. The less symmetric structure of $\text{Bi}_2\text{Ti}_4\text{O}_{11}$ than $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ can be simply explained by that Bi^{3+} cations are more positive than Pb^{2+} cations and prefer to be closer to anions. In the case of $\text{Bi}_2\text{Ti}_4\text{O}_{11}$, the steric effects of $6s^2$ lone pairs may also contribute to the low-symmetric anionic configurations as discussed based on the MEM analyses in the ESI.† The finding from Table 2 demonstrates that the influence of $6s^2$ lone pairs on the structural distortion might be similarly not significant in some of the other Pb-based oxyfluorides such as $\text{Pb}_2\text{Ti}_2\text{O}_{5.4}\text{F}_{1.2}$ ²⁹ and Pb_2OF_2 .³⁰

5 Conclusion

A combination of ^{19}F MAS NMR experiments and DFT simulations were used to investigate the anionic ordering in

$\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$. The ^{19}F MAS NMR experiments showed that F atoms predominantly occupy two of the six distinct available sites in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ in a ratio of 73 : 27. DFT calculations identified the majority and minority F occupation sites to be sites 6 and 5, respectively. The occupation ratios between sites 6 and 5 were quantitatively reproduced by theory, independent of the choice of functional. PDOS and COHP analyses revealed that the $6s^2$ lone pairs of Pb atom may play a role (~ 0.1 eV per f.u.) in determining the site 6 (5) the majority (minority) site, against what is predicted by Pauling's second rule.²⁸

The low-symmetric anionic coordinates around the cations in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ have been considered to be the consequence of the steric effect by the $6s^2$ lone pairs, as well as $\text{Bi}_2\text{Ti}_4\text{O}_{11}$,³² $\text{Pb}_2\text{Ti}_2\text{O}_{5.4}\text{F}_{1.2}$,²⁹ and some Aurivillius oxides $\text{ABi}_2\text{Nb}(\text{Ta})_2\text{O}_9$.⁵² However, our DFT results indicate that the $6s^2$ lone pairs may barely induce a structural distortion in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$. This finding demonstrates that the influence of $6s^2$ lone pairs on the structural distortion might be similarly not significant in some of the other Pb-based oxyfluorides such as $\text{Pb}_2\text{Ti}_2\text{O}_{5.4}\text{F}_{1.2}$ ²⁹ and Pb_2OF_2 .³⁰

Author contributions

K.O., T.I., and D.K. conceived the ideas of this work. All the authors contributed to the discussion and writing of the paper. K.O. and K.Y. synthesized the $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$ and $\text{Bi}_2\text{Ti}_4\text{O}_{11}$ samples, analyzed the crystal structures, and performed MEM analyses. Y.N., Y.T., and N.N. performed the ^{19}F MAS NMR measurements. T.I., D.K., and K.H. performed the *ab initio* calculations. M.I., R.M., and F.A.R. supervised the work.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors acknowledge Erica Heinrich for valuable help with manuscript preparation. The VESTA program⁵³ was used to visualize the experimental and DFT crystal structures and electronic densities. The authors thank Prof. Sudo and Mr.



Kitao of Kindai University for their help in the solid state NMR measurement. This work was partially supported by a Grant-in-Aid for Scientific Research on Innovative Area "Mixed Anion (Project JP17H05489, JP19H04706)" (JSPS). The synchrotron radiation experiments were performed at the BL02B2 of SPring-8 with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) (Proposal No. 2016A1157 and 2018A1227). The *ab initio* calculations were performed with the computational resources of the Research Center for Advanced Computing Infrastructure (RCACI) at JAIST. The authors gratefully thank Division of Joint Research Center, Kindai University, for the solid-state NMR measurements. T. I. and F. A. R. acknowledge support from US Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division. K. O. is grateful for financial support from Kansai Research Foundation for technology promotion and a Grant-in-Aids for Scientific Research (C) (Project JP16K05731 and 21K04659). K. H. is grateful for financial support from MEXT-KAKENHI (JP19K05029, JP21K03400, JP21H01998, and JP22H02170), and the Air Force Office of Scientific Research (Award Numbers: FA2386-20-1-4036). R. M. is grateful for financial supports from MEXT-KAKENHI (22H05146, 21K03400 and 19H04692), from the Air Force Office of Scientific Research (AFOSR-AOARD/FA2386-17-1-4049; FA2386-19-1-4015), and from JSPS Bilateral Joint Projects (JPJSBP120197714).

References

- H. Kageyama, T. Yajima, Y. Tsujimoto, T. Yamamoto, C. Tassel and Y. Kobayashi, Exploring Structures and Properties through Anion Chemistry, *Bull. Chem. Soc. Jpn.*, 2019, **92**, 1349–1357.
- K. Maeda, F. Takeiri, G. Kobayashi, S. Matsuishi, H. Ogino, S. Ida, T. Mori, Y. Uchimoto, S. Tanabe, T. Hasegawa, N. Imanaka and H. Kageyama, Recent Progress on Mixed-Anion Materials for Energy Applications, *Bull. Chem. Soc. Jpn.*, 2022, **95**, 26–37.
- H. Kageyama, K. Hayashi, K. Maeda, J. P. Attfield, Z. Hiroi, J. M. Rondinelli and K. R. Poeppelmeier, Expanding frontiers in materials chemistry and physics with multiple anions, *Nat. Commun.*, 2018, **9**, 772.
- R. Kuriki, T. Ichibha, K. Hongo, D. Lu, R. Maezono, H. Kageyama, O. Ishitani, K. Oka and K. Maeda, A Stable, Narrow-Gap Oxyfluoride Photocatalyst for Visible-Light Hydrogen Evolution and Carbon Dioxide Reduction, *J. Am. Chem. Soc.*, 2018, **140**, 6648–6655.
- T. Oshima, T. Ichibha, K. S. Qin, K. Muraoka, J. J. M. Vequizo, K. Hibino, R. Kuriki, S. Yamashita, K. Hongo, T. Uchiyama, K. Fujii, D. Lu, R. Maezono, A. Yamakata, H. Kato, K. Kimoto, M. Yashima, Y. Uchimoto, M. Kakihana, O. Ishitani, H. Kageyama and K. Maeda, Undoped Layered Perovskite Oxynitride $\text{Li}_2\text{LaTa}_2\text{O}_6\text{N}$ for Photocatalytic CO_2 Reduction with Visible Light, *Angew. Chem., Int. Ed.*, 2018, **57**, 8154–8158.
- T. Oshima, T. Ichibha, K. Oqmhula, K. Hibino, H. Mogi, S. Yamashita, K. Fujii, Y. Miseki, K. Hongo, D. Lu, R. Maezono, K. Sayama, M. Yashima, K. Kimoto, H. Kato, M. Kakihana, H. Kageyama and K. Maeda, Two-Dimensional Perovskite Oxynitride $\text{K}_2\text{LaTa}_2\text{O}_6\text{N}$ with an H^+/K^+ Exchangeability in Aqueous Solution Forming a Stable Photocatalyst for Visible-Light H_2 Evolution, *Angew. Chem., Int. Ed.*, 2020, **59**, 9736–9743.
- Y.-I. Kim, P. M. Woodward, K. Z. Baba-Kishi and C. W. Tai, Characterization of the Structural, Optical, and Dielectric Properties of Oxynitride Perovskites AMO_2N ($\text{A} = \text{Ba}, \text{Sr}, \text{Ca}$; $\text{M} = \text{Ta}, \text{Nb}$), *Chem. Mater.*, 2004, **16**, 1267–1276.
- K. Page, M. W. Stoltzfus, Y.-I. Kim, T. Proffen, P. M. Woodward, A. K. Cheetham and R. Seshadri, Local Atomic Ordering in BaTaO_2N Studied by Neutron Pair Distribution Function Analysis and Density Functional Theory, *Chem. Mater.*, 2007, **19**, 4037–4042.
- M. Yang, J. Oró-Solé, J. A. Rodgers, A. B. Jorge, A. Fuertes and J. P. Attfield, Anion order in perovskite oxynitrides, *Nat. Chem.*, 2010, **3**, 47–52.
- T. Yamamoto, D. Zeng, T. Kawakami, V. Arcisauskaitė, K. Yata, M. A. Patino, N. Izumo, J. E. McGrady, H. Kageyama and M. A. Hayward, The role of π -blocking hydride ligands in a pressure-induced insulator-to-metal phase transition in SrVO_2H , *Nat. Commun.*, 2017, **8**, 1217.
- J. P. Attfield, Principles and Applications of Anion Order in Solid Oxynitrides, *Cryst. Growth Des.*, 2013, **13**, 4623–4629.
- A. Fuertes, Prediction of Anion Distributions Using Pauling's Second Rule, *Inorg. Chem.*, 2006, **45**, 9640–9642.
- C. M. Thompson, C. K. Blakely, R. Flacau, J. E. Greedan and V. V. Poltavets, Structural and magnetic behavior of the cubic oxyfluoride SrFeO_2F studied by neutron diffraction, *J. Solid State Chem.*, 2014, **219**, 173–178.
- F. J. Berry, F. C. Coomer, C. Hancock, O. Helgason, E. A. Moore, P. R. Slater, A. J. Wright and M. F. Thomas, Structure and magnetic properties of the cubic oxide fluoride BaFeO_2F , *J. Solid State Chem.*, 2011, **184**, 1361–1366.
- T. Katsumata, M. Nakashima, H. Umemoto and Y. Inaguma, Synthesis of the novel perovskite-type oxyfluoride PbScO_2F under high pressure and high temperature, *J. Solid State Chem.*, 2008, **181**, 2737–2740.
- R. L. Needs and M. T. Weller, A New $2+/3+$ Perovskite: The Synthesis and Structure of BaScO_2F , *J. Solid State Chem.*, 1998, **139**, 422–423.
- F. Takeiri, T. Yamamoto, N. Hayashi, S. Hosokawa, K. Arai, J. Kikkawa, K. Ikeda, T. Honda, T. Otomo, C. Tassel, K. Kimoto and H. Kageyama, AgFeOF_2 : A Fluorine-Rich Perovskite Oxyfluoride, *Inorg. Chem.*, 2018, **57**, 6686–6691.
- T. Katsumata, R. Suzuki, N. Satoh, S. Suzuki, M. Nakashima, Y. Inaguma, D. Mori, A. Aimi and Y. Yoneda, Synthesis of new perovskite-type oxyfluorides, BaInO_2F and comparison of the structure among perovskite-type oxyfluorides, *J. Solid State Chem.*, 2019, **279**, 120919.



- 19 Y. Inaguma, K. Sugimoto and K. Ueda, Synthesis of the perovskite-type oxyfluoride AgTiO_2F : an approach adopting the HSAB principle, *Dalton Trans.*, 2020, **49**, 6957–6963.
- 20 M. Ai-Mamouri, P. P. Edwards, C. Greaves and M. Slaski, Synthesis and superconducting properties of the strontium copper oxy-fluoride $\text{Sr}_2\text{CuO}_2\text{F}_{2+\delta}$, *Nature*, 1994, **369**, 382–384.
- 21 G. Simon Case, A. L. Hector, W. Levason, R. L. Needs, M. F. Thomas and M. T. Weller, Syntheses, powder neutron diffraction structures and Mössbauer studies of some complex iron oxyfluorides: $\text{Sr}_3\text{Fe}_2\text{O}_6\text{F}_{0.87}$, $\text{Sr}_2\text{FeO}_3\text{F}$ and $\text{Ba}_2\text{InFeO}_5\text{F}_{0.68}$, *J. Mater. Chem.*, 1999, **9**, 2821–2827.
- 22 A. L. Hector, J. A. Hutchings, R. L. Needs, M. F. Thomas and M. T. Weller, Structural and Mössbauer study of $\text{Sr}_2\text{FeO}_3\text{X}$ ($\text{X} = \text{F}, \text{Cl}, \text{Br}$) and the magnetic structure of $\text{Sr}_2\text{FeO}_3\text{F}$, *J. Mater. Chem.*, 2001, **11**, 527–532.
- 23 R. L. Needs and M. T. Weller, Synthesis and structure of $\text{Ba}_2\text{InO}_3\text{F}$: oxide/fluoride ordering in a new K_2NiF_4 superstructure, *J. Chem. Soc., Chem. Commun.*, 1995, 353–354.
- 24 R. L. Needs, M. T. Weller, U. Scheler and R. K. Harris, Synthesis and structure of $\text{Ba}_2\text{InO}_3\text{X}$ ($\text{X} = \text{F}, \text{Cl}, \text{Br}$) and $\text{Ba}_2\text{ScO}_3\text{F}$; oxide/halide ordering in K_2NiF_4 -type structures, *J. Mater. Chem.*, 1996, **6**, 1219–1224.
- 25 Y. Su, Y. Tsujimoto, Y. Matsushita, Y. Yuan, J. He and K. Yamaura, High-Pressure Synthesis, Crystal Structure, and Magnetic Properties of $\text{Sr}_2\text{MnO}_3\text{F}$: A New Member of Layered Perovskite Oxyfluorides, *Inorg. Chem.*, 2016, **55**, 2627–2633.
- 26 Y. Tsujimoto, K. Yamaura, N. Hayashi, K. Kodama, N. Igawa, Y. Matsushita, Y. Katsuya, Y. Shirako, M. Akaogi and E. Takayama-Muromachi, Topotactic Synthesis and Crystal Structure of a Highly Fluorinated Ruddlesden-Popper-Type Iron Oxide, $\text{Sr}_3\text{Fe}_2\text{O}_{5+x}\text{F}_{2-x}$ ($x \sim 0.44$), *Chem. Mater.*, 2011, **23**, 3652–3658.
- 27 L.-S. Du, F. Wang and C. P. Grey, High-Resolution ^{19}F MAS and ^{19}F – ^{113}Cd REDOR NMR Study of Oxygen/Fluorine Ordering in Oxyfluorides, *J. Solid State Chem.*, 1998, **140**, 285–294.
- 28 L. Pauling, *The nature of the chemical bond and the structure of molecules and crystals: an introduction to modern structural chemistry*, Cornell University Press, Ithaca, N.Y., 1960, pp. 543–562.
- 29 K. Oka, H. Hojo, M. Azuma and K. Oh-ishi, Temperature-Independent, Large Dielectric Constant Induced by Vacancy and Partial Anion Order in the Oxyfluoride Pyrochlore $\text{Pb}_2\text{Ti}_2\text{O}_{6-\delta}\text{F}_{2\delta}$, *Chem. Mater.*, 2016, **28**, 5554–5559.
- 30 Y. Inaguma, K. Ueda, T. Katsumata and Y. Noda, Low-temperature formation of Pb_2OF_2 with O/F anion ordering by solid state reaction, *J. Solid State Chem.*, 2019, **277**, 363–367.
- 31 K. Oka and K. Oh-ishi, Observation of Anion Order in $\text{Pb}_2\text{Ti}_4\text{O}_9\text{F}_2$, *Inorg. Chem.*, 2015, **54**, 10239–10242.
- 32 V. Kahlenberg and H. Böhm, The structures of α - and β - $\text{Bi}_2\text{Ti}_4\text{O}_{11}$, *Acta Crystallogr., Sect. B: Struct. Sci.*, 1995, **51**, 11–18.
- 33 T. Katsumata, M. Nakashima, Y. Inaguma and T. Tsurui, Synthesis of New Perovskite-Type Oxyfluoride, PbMnO_2F , *Bull. Chem. Soc. Jpn.*, 2012, **85**, 397–399.
- 34 S. Kawaguchi, M. Takemoto, K. Osaka, E. Nishibori, C. Moriyoshi, Y. Kubota, Y. Kuroiwa and K. Sugimoto, High-throughput powder diffraction measurement system consisting of multiple MYTHEN detectors at beamline BL02B2 of SPring-8, *Rev. Sci. Instrum.*, 2017, **88**, 085111.
- 35 F. Izumi and K. Momma, Three-Dimensional Visualization in Powder Diffraction, *Solid State Phenomena*, 2007, **130**, 15–20.
- 36 K. Momma, T. Ikeda, A. A. Belik and F. Izumi, Dysnomia, a computer program for maximum-entropy method (MEM) analysis and its performance in the MEM-based pattern fitting, *Powder Diffr.*, 2013, **28**, 184–193.
- 37 P. Giannozzi, S. Baroni, N. Bonini, M. Calandra, R. Car, C. Cavazzoni, D. Ceresoli, G. L. Chiarotti, M. Cococcioni, I. Dabo, A. D. Corso, S. de Gironcoli, S. Fabris, G. Fratesi, R. Gebauer, U. Gerstmann, C. Gougoussis, A. Kokalj, M. Lazzeri, L. Martin-Samos, N. Marzari, F. Mauri, R. Mazzarello, S. Paolini, A. Pasquarello, L. Paulatto, C. Sbraccia, S. Scandolo, G. Sclauzero, A. P. Seitsonen, A. Smogunov, P. Umari and R. M. Wentzcovitch, QUANTUM ESPRESSO: a modular and open-source software project for quantum simulations of materials, *J. Phys.: Condens. Matter*, 2009, **21**, 395502.
- 38 J. P. Perdew, K. Burke and M. Ernzerhof, Generalized Gradient Approximation Made Simple, *Phys. Rev. Lett.*, 1996, **77**, 3865–3868.
- 39 A. D. Becke, Density-functional exchange-energy approximation with correct asymptotic behavior, *Phys. Rev. A*, 1988, **38**, 3098–3100.
- 40 C. Lee, W. Yang and R. G. Parr, Development of the Colle-Salvetti correlation-energy formula into a functional of the electron density, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1988, **37**, 785–789.
- 41 J. P. Perdew and Y. Wang, Accurate and simple analytic representation of the electron-gas correlation energy, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1992, **45**, 13244–13249.
- 42 J. P. Perdew and Y. Wang, Erratum: Accurate and simple analytic representation of the electron-gas correlation energy [Phys. Rev. B 45, 13244 (1992)], *Phys. Rev. B*, 2018, **98**, 079904.
- 43 G. Kresse and D. Joubert, From ultrasoft pseudopotentials to the projector augmented-wave method, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1999, **59**, 1758–1775.
- 44 A. Dal Corso, Pseudopotentials periodic table: From H to Pu, *Comput. Mater. Sci.*, 2014, **95**, 337–350.
- 45 P. E. Blöchl, Projector augmented-wave method, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1994, **50**, 17953–17979.
- 46 R. Nelson, C. Ertural, J. George, V. L. Deringer, G. Hautier and R. Drnonskowski, LOBSTER: Local orbital projections, atomic charges, and chemical-bonding analysis from projector-augmented-wave-based density-functional theory, *J. Comput. Chem.*, 2020, **41**, 1931–1940.



- 47 S. Maintz, V. L. Deringer, A. L. Tchougréeff and R. Dronskowski, Analytic projection from plane-wave and PAW wavefunctions and application to chemical-bonding analysis in solids, *J. Comput. Chem.*, 2013, **34**, 2557–2567.
- 48 S. Maintz, V. L. Deringer, A. L. Tchougréeff and R. Dronskowski, LOBSTER: A tool to extract chemical bonding from plane-wave based DFT, *J. Comput. Chem.*, 2016, **37**, 1030–1035.
- 49 Y. Kurauchi, T. Katayama, A. Chikamatsu and T. Hasegawa, Two-Dimensional Fluorine Distribution in a Heavily Distorted Perovskite Nickel Oxyfluoride Revealed by First-Principles Calculation, *J. Phys. Chem. C*, 2019, **123**, 31190–31195.
- 50 A. Walsh, D. J. Payne, R. G. Egddell and G. W. Watson, Stereochemistry of post-transition metal oxides: revision of the classical lone pair model, *Chem. Soc. Rev.*, 2011, **40**, 4455–4463.
- 51 D. Lee and H. N. Lee, Controlling Oxygen Mobility in Ruddlesden–Popper Oxides, *Materials*, 2017, **10**, 368.
- 52 Ismunandar and B. J. Kennedy, Gunawan and Marsongkohadi, Structure of $\text{ABi}_2\text{Nb}_2\text{O}_9$ (A = Sr, Ba): Refinement of Powder Neutron Diffraction Data, *J. Solid State Chem.*, 1996, **126**, 135–141.
- 53 K. Momma and F. Izumi, VESTA 3 for three-dimensional visualization of crystal, volumetric and morphology data, *J. Appl. Crystallogr.*, 2011, **44**, 1272–1276.

