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Theoretical study of ternary silver fluorides AgMF_4 ($\text{M} = \text{Cu}, \text{Ni}, \text{Co}$) formation at pressures up to 20 GPa^{†‡}

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Only several compounds bearing the Ag(II) cation and other paramagnetic transition metal cations are known experimentally. Herein, we predict *in silico* stability and crystal structures of hypothetical ternary silver(II) fluorides with copper, nickel and cobalt in 1 : 1 stoichiometry at a pressure range from 0 GPa up to 20 GPa employing the evolutionary algorithm in combination with DFT calculations. The calculations show that AgCoF_4 could be synthesized already at ambient conditions but this compound would host diamagnetic Ag(I) and high-spin Co(III). Although none of the compounds bearing Ag(II) could be preferred over binary substrates at ambient conditions, at increased pressure ternary fluorides of Ag(II) featuring Cu(II) and Ni(II) could be synthesized, in the pressure windows of 7–14 and 8–15 GPa, respectively. All title compounds would be semiconducting and demonstrate magnetic ordering. Compounds featuring Ni(II) and particularly Co(II) should exhibit fundamental band gaps much reduced with respect to pristine AgF_2 . The presence of Cu(II) and Ni(II) does not lead to electronic doping to AgF_2 layers, while Co(II) tends to reduce Ag(II) entirely to Ag(I).

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Introduction

Recent experimental and theoretical research on AgF_2 demonstrated that this material mimics very closely the key structural and electronic properties of the well-known lanthanum oxocuprate La_2CuO_4 (ref. 1) – the prototype precursor of high-temperature oxocuprate superconductors – that are believed to be a necessary prerequisite for the unique behaviour of the latter. They account for strong antiferromagnetic coupling *via* a superexchange mechanism in two-dimensional sheets² and substantial mixing of ligand and metal states in the top of the valence band. Superconductivity is reached in the oxocuprates *via* chemical doping and because of the striking similarities, not observed in any other known compound, it was suggested that superconductivity could be obtained also in the related silver(II) fluorides if proper chemical doping to AgF_2 that would lead to metallization could be realized.^{1,3,4} It is therefore highly desirable to examine various possibilities to modify its electronic and magnetic properties *via* doping.

Doping in essence is equivalent to the insertion of surplus holes or electrons into the chemical system. However, in contrast to cuprates, the bulk AgF_2 has so far resisted all doping attempts. The hole doping of AgF_2 could be introduced by F adatoms, but theoretical studies show that doping to this 001-type system *via* the addition of F atoms does not lead to a stable metallic phase.⁵ Partial oxidation of Ag(II) is also difficult, due to the immensely strong oxidative character of Ag(III); compounds of Ag(III) are even more difficult to synthesize and manipulate than Ag(II) compounds.

Therefore, our attention turned to electron doping, which could be introduced in two general ways. The first one is provided by vacancies at anionic sites ($\text{AgF}_2 \rightarrow \text{AgF}_{2-\delta}$). Similarly, as with additional F^- , the study shows that the vacancies lead to clustering and phase separation without the prospect of obtaining a metallic phase.⁵ The second possibility, that we focus on here, is to modify AgF_2 *via* substitution at the cationic site injecting the surplus electron. Early attempts to dope ternary silver fluorides (*e.g.* KAgF_3) in a manner analogous to cuprates, *i.e.* substituting partially M(I) cations with M(II), failed. Recent theoretical investigations suggest that electron doping to AgF_2 would not lead to a stable metallic phase due to a lattice polaronic effect and charge localization.⁶ Therefore the remaining way to achieve electron doping in AgF_2 is to try partial isostructural substitution of Ag(II). By this, we mean to replace square planar Ag(II) in AgF_2 with another redox-active metal cation, M(II), so that the layered structure is preserved but the electrons may partly flow from M(II) to Ag(II). This type of doping has not been yet achieved experimentally. Thus, in this

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[†] This work is dedicated to Prof. Gary Schrobilgen at his 75th birthday.

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study, we explored new ternary phases bearing Ag(II), especially isostructural to AgF₂, to learn to what extent could the electronic structure of AgF₂ sheets be altered by the presence of other metal cations.

The natural choice for the M element is a transition metal which also presents octahedral coordination featuring Jahn–Teller distortion like Ag(II). Accordingly, we considered diverse ternary fluoride stoichiometries which may host strongly coupled AgF₂ sheets. Among ternary fluorides Ag^{II}M_xF_y, many transition metal systems have been successfully prepared so far,³ *i.e.* for M = Au(III), Au(V), Nb(V), Ta(V), Ti(IV), Zr(IV), Hf(IV), Ru(V), Rh(IV), Ir(V), Pd(IV), Pt(IV), Pt(V), Mn(IV) and Cr(IV) (AgMn^{IV}F₆ (ref. 7) and AgCr^{IV}F₆ (ref. 8) structures not known). None of these fluorides host [AgF₂] sheets or chains required for achieving strong antiferromagnetic coupling. Yet the great majority of these compounds contain closed-shell or low-spin cations which would not hold any magnetic interactions.

Late 3d-block transition metals, especially Cu, Ni and Co, seem to be promising candidates for electron doping due to their relative resistance towards oxidation in the fluoride environment while having partly filled d subshell. The redox potentials for the M^{3+/2+} redox pairs decrease in the Cu > Ni > Co sequence. Experimentally, CoF₃ and NiF₃ (actually Ni^{II}Ni^{IV}F₄ (ref. 9)) are moderately stable in an inert atmosphere, and they constitute strong fluorinating agents. On the other hand, CuF₃ is quite unstable thermally and thermodynamically¹⁰ (even more than AgF₃ (ref. 11)), thus minimizing the possibility of the intrinsic redox reaction between Ag(II) and Cu(II). Remarkably, such appealing synthesis has not been achieved experimentally yet, so no fluorides having Ag(II) and M(II) (M = Cu, Ni, Co) in any ratio are known, despite many similarities between these cations. There are, however, some examples of compounds with Ag(I) and M(III) valences. Among fluoride systems, only the Ag(I) Co(III) fluoride with Ag₃CoF₆ formula has been already described,¹² suggesting that as yet unobserved Ag(II)Co(II) pair might be just beyond the border of intrinsic redox reaction. Silver fluorides with M = Cu or Ni are not known, thus the forms bearing Ag(II) and M(II) or Ag(I) and M(III) can not be excluded. Furthermore, there are known ternary oxide systems having Ag(I) and M(III) with AgMO₂ formula (M = Cu, Ni, Co).^{13–17} Oxide and fluoride systems of silver tend to differ dramatically, thus the question about the nature of the late 3d ternary fluorides remains open.

The theoretical search for ternary systems bearing initially divalent cations has the aim of verification if it could possibly form a metallic phase with Ag(II). Since ternary oxides with Ag : M ratio of 1 : 1 are known, here we decided to study ternary fluorides with the same ratio. To understand whether ternary fluorides bearing Ag(II) in combination with another transition metal (TM) constitute a viable synthetic target, we have examined here AgMF₄ systems with Cu, Ni and Co using Density Functional Theory (DFT) methods in combination with evolutionary algorithms for crystal structures' prediction.

Preliminary results showed that such systems are very close in terms of energy to the sum of binary substrates but have lower volume, suggesting they could be obtained at elevated pressures. It is well-known that pressure may affect to a great

extent both the crystal structures and stability of chemical compounds.¹⁹ High-pressure synthesis proved to be crucial in the synthesis of some transition metal compounds, *e.g.* copper oxyfluorides¹⁸ (and references therein), as well as for inducing metallization,^{19,20} the latter being not possible in pure AgF₂.²¹ Thus, aside from variations of the chemical composition, we also study the impact of external pressure on crystal and electronic structure, and stability of AgMF₄ systems with respect to the mixture of binary fluorides, AgF₂ and MF₂ (M = Cu, Ni, Co). Since both stability and electronic properties may depend on pressure, we have investigated the effect of external pressure on the formation and properties of the title AgMF₄ compounds.

Computational methods

This theoretical study is based on periodic electronic-structure calculations for solids carried out with Vienna *Ab initio* Simulation Package 5.4.4 (VASP) software using projector-augmented wave method.^{22–24} We used the potentials set recommended by VASP with a 520 eV plane-wave energy cut-off. Energy calculations utilized collinearly spin-polarized DFT method using generalized gradient approximation functional PBEsol (*i.e.* solid-revised Perdew, Burke and Ernzerhof correlation–exchange functional²⁵). The on-site electronic correlation was included with Hubbard and exchange repulsion terms (*U* and *J*) using Dudarev's approach.^{26,27} Geometry optimizations were done with *k*-spacing of $2\pi \times 0.024 \text{ \AA}^{-1}$ (using the Monkhorst–Pack scheme) and conjugate-gradient algorithm for ionic relaxation with the criteria of 10^{-7} eV for electronic self-consistent-field convergence and 10^{-5} eV for ionic cycles convergence. In this approach effective $U_{\text{eff}} = U - J$, is considered, thus we used U_{eff} equal 4 eV (for Ag, Ni), 5 eV (Co) and 8 (Cu). These values were earlier used and validated in respective systems exhibiting +II oxidation state.^{2,28–30}

In our quest for the lowest-energy crystal structure of hypothetical compounds of AgCuF₄, AgNiF₄ and AgCoF₄, we have initially tested various substitutions within the known crystal structure of AgF₂. We have tested also various prototypical M^IM^{III}F₄ structures, which allow for electron transfer between metal sites; notably, we presumed that electron-hungry Ag(II) could undergo reduction, with the concomitant 1 – e[–] oxidation of its neighbouring TM cations. The three scrutinized 3d elements, Cu, Ni and Co, differ in terms of redox properties, electron count, *U*-induced splitting of upper and lower Hubbard d-bands, and degree of tetragonal distortion of MF₆ octahedra. All above-mentioned cations also have significantly smaller cationic radii than Ag(II). AgMF₄ (M = Cu, Ni, Co) fluorides were modelled in the appropriate ABC₄ structure types selected from the Inorganic Crystal Structure Database (ICSD). Furthermore, in each case, we have searched for the global minimum structure using evolutionary algorithms (EA) as implemented in the XtalOpt software³³ for crystal structure prediction. The starting pool (*i.e.* 1st generation) for each XtalOpt run constituted 30 initial random structures containing 2 or 4 formula units in the unit cell. After the pool of structures is optimized by VASP, XtalOpt selects the best possible candidates for the next generation, employs such operators as strain, exchange, ripple,



and crossover on the selected candidates, which form the next generation of structures. Such structure generation and optimization continue until the energy convergence is reached. The XtalOpt runs were performed for the three title stoichiometries of AgMF_4 , at 0 and 10 GPa considering unit cells containing 2 to 4 formula units. XtalOpt runs were done in combination with DFT calculations using VASP optimizer. A four-step optimization procedure of each structure was performed increasing accuracy at each step, using DFT for the first two and DFT+U (*i.e.* with Dudarev's approach) approach for the last two steps. These calculations were performed with reduced convergence criteria (5×10^{-7} eV and 5×10^{-5} eV for the electronic and ionic cycle, respectively) and k -point mesh ($2\pi \times 0.048 \text{ \AA}^{-1}$). For each system, we have obtained about optimized 500 structures (more in ESI, see Fig. S1 and S2[†]). The selected lowest-energy EA structures were reoptimized with higher precision as described above. The XtalOpt is a robust tool that has been utilized more than sixty times in solid-state chemistry or physics applications.³⁴

For selected systems, geometry optimization was additionally performed using the HSE06 hybrid functional³⁵ with a coarser k -spacing ($2\pi \times 0.048 \text{ \AA}^{-1}$). For the chosen systems we calculated the electronic density of states (DOS) with tetrahedron method and Blöchl corrections, with both DFT+U and HSE06.

Dynamic stability was investigated in VASP by calculating T -point vibrational frequencies, using the density functional perturbation theory method and the DFT+U framework.

For visualization of crystal structures, VESTA³⁶ software was used. Band structure plots were made using PyProcar library³⁷ and AFLOW³⁸ program.

Results and discussion

The idea of pressure study originates from preliminary results, as numerous low-volume polymorphs have already been identified in the XtalOpt quest at ambient pressure (Fig. S1a, c and e[†]). Consequently, we have studied the AgMF_4 phases in a range of hydrostatic pressure with the prospect of obtaining pressure-induced stability of AgMF_4 ($M = \text{Cu}, \text{Ni}$ and Co) in respect to

binary substrates AgF_2 and MF_2 , and to evaluate the possibility of high-pressure metallization of the ternary silver(II) fluorides. The formation enthalpy of the lowest-energy polymorphs from the substrates was investigated in the 0–20 GPa pressure range. The pressure evolution for AgMF_4 systems with respect to the sum of those for the binary substrates in their most stable polymorphs is presented in Fig. 1. With our choice of U_{eff} we successfully confirmed the experimentally observed pressure-induced phase transitions of AgF_2 ,²¹ CuF_2 ,³¹ NiF_2 (ref. 32) and CoF_2 (ref. 28 and 32) up to 20 GPa (note in ESI, see also Table S1 and Fig. S3,[†] these phase transitions are marked in Fig. 1). The phase-transition sequences in the considered stoichiometries were calculated with the described DFT+U framework assuming hydrostatic conditions.

Additional insight into pressure-induced effects on the enthalpy of formation of the ternary fluorides comes from pV term analysis (ESI, Fig. S4[†]). Both for low pressure (<3 GPa) and high-pressure range (>9 GPa) the pV factor works against the formation of the studied ternary fluoride phases. Consequently, the ternary fluoride phases benefit from the pV term with respect to the substrates in the range 3–9 GPa; at higher pressures, binary substrates experience volume-reducing phase transitions which reduces this advantage. The crucial is the phase transition of constituent AgF_2 at about 14 GPa into an unprecedented inorganic nanotube.²¹ This incredibly low-volume polymorph reduces the pV term of substrates and gradually destabilizes thermodynamically all proposed ternary fluorides at pressures approaching 20 GPa. These factors result in re-entrant instability of the ternary phases above certain characteristic pressure in each case.

The hypothetical mixed-cation AgMF_4 fluorides from Fig. 1 are below described in the order of $M = \text{Cu}, \text{Ni}, \text{Co}$, in terms of their structure and stability, and then of the pressure effects. Finally, we investigate their electronic properties at ambient and elevated pressures.

Copper

Ambient pressure. Due to the similar chemistry of Ag(II) and Cu(II) , as well as similar crystal structures of binary fluorides,

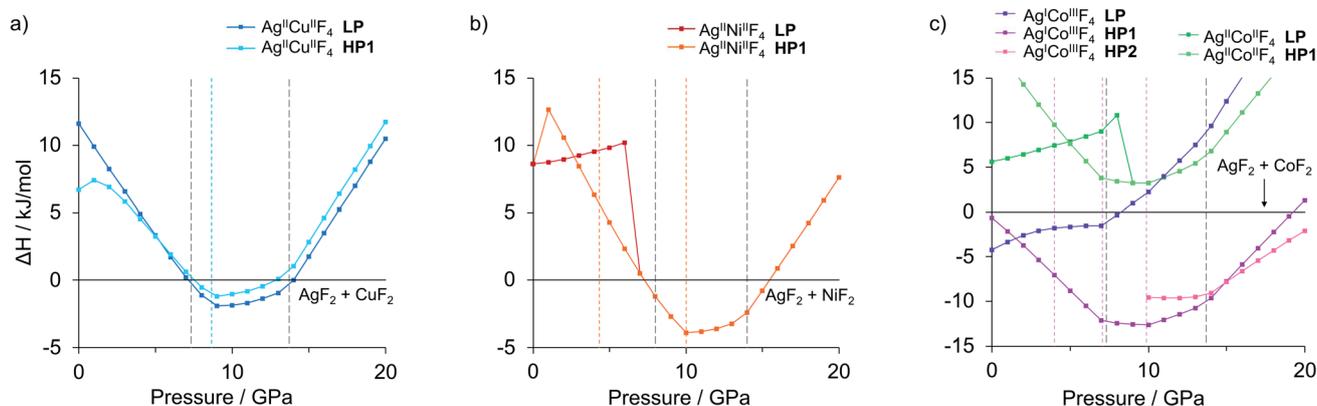


Fig. 1 Calculated relative enthalpy of ternary silver fluorides AgMF_4 (a) $M = \text{Cu}$, (b) $M = \text{Ni}$, (c) $M = \text{Co}$, with respect to lowest-enthalpy polymorphic forms of binary fluorides at each given pressure point. All the lowest enthalpy $\text{Ag(II)}-\text{M(II)}$ fluorides comprise M -half-substituted AgF_2 type structures. Vertical dashed lines indicate phase transitions calculated for the MF_2 substrates.



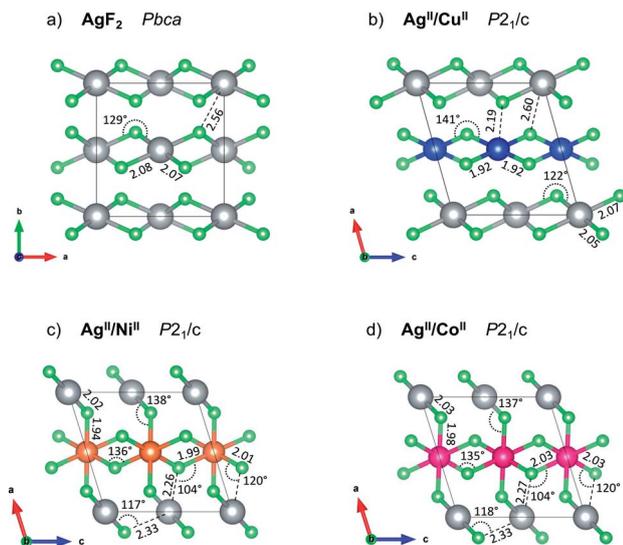


Fig. 2 Crystal structures of (a) parent AgF_2 , the lowest-energy predicted (b) AgCuF_4 , and (c) AgNiF_4 , and metastable (d) $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ at ambient pressure (LP structure of each). The threshold for Ag–F bond drawing is 2.15 Å in all cases. All bond lengths provided in angstroms, and angles in degrees. Grey for silver atoms, green for fluorine, blue for copper, orange for nickel and magenta for cobalt.

our primary candidate for the AgCuF_4 structure was the orthorhombic layered structure typical of AgF_2 (ref. 39) (Fig. 2a). Three types of substitutions at the metal site were considered, *i.e.* metal alternation in the directions perpendicular to the \vec{a} , \vec{b} or \vec{c} lattice vectors (*cf.* ESI, Fig. S5 \ddagger). Notably, these three diverse polymorphs were also found during EA search (see ESI, Fig. S1 and S2 \ddagger). We found that a monoclinic variant of the AgF_2 type structure with metal alternation in the original b direction is the lowest-energy structure of AgCuF_4 (marked here as low-pressure, LP, structure, Fig. 2b), as confirmed by evolutionary algorithm quest. This polymorph preserves the layered character of its binary constituents by separating Ag and Cu into distinct puckered $[\text{AgF}_{4/2}]$ and $[\text{CuF}_{4/2}]$ layers. Substantial axial elongation of both $\text{Ag}(\text{II})$ and $\text{Cu}(\text{II})$ octahedra is predicted (*i.e.* four shorter equatorial and two considerably longer axial Ag(Cu)–F distances (2 + 2) + 2 coordination), in agreement with the strong Jahn–Teller effect which is expected for d^9 species in

octahedral field. The rhombic distortion can be approximated to tetragonal distortion (4) + 2 in most cases. The ratio of axial to equatorial bond lengths $R = d_{\text{ax}}/d_{\text{eq}}$ (dimensionless Jahn–Teller distortion parameter often used to describe such compounds⁴⁰) equals 1.24 for the $\text{Ag}(\text{II})$ site and 1.14 for the $\text{Cu}(\text{II})$ one. The tetragonal distortion for both cations is similar as in the parent phases where this ratio equals 1.23 and 1.15, for AgF_2 and CuF_2 , respectively (all geometry parameters are summarised in Table 1).

Axial elongation suggests that in both cations d-hole occupies $d_{x^2-y^2}$ orbital. Both constituent layers $[\text{AgF}_{4/2}]$ and $[\text{CuF}_{4/2}]$ of AgCuF_4 preserve intra-sheet antiferromagnetic ordering.

The geometry within the puckered layers is reminiscent of those found in binary fluorides; the $[\text{AgF}_{4/2}]$ layers are more buckled than in pure AgF_2 (the Ag–F–Ag angle is 122° vs. 129° in bulk AgF_2), while $[\text{CuF}_{4/2}]$ layers are flattened (the corresponding angle is 141° vs. 132° in bulk CuF_2). This feature stems from the difference in the ionic radii between $\text{Ag}(\text{II})$ and $\text{Cu}(\text{II})$. In order to form a segregated layer structure, the $[\text{AgF}_2]$ sheets must buckle and the $[\text{CuF}_2]$ sheets must simultaneously flatten; this accommodation is associated by bending of the crystallographic beta angle from 90° (for bulk AgF_2) to 105° . We notice that two other models with mixed $[(\text{Ag,Cu})\text{F}_{4/2}]$ layers (ESI, Fig. S5c and d \ddagger), have energies higher by +6.4 and +7.3 kJ mol^{-1} , respectively, as compared to the LP structure. We also found a crystal structure containing Ag–F–Cu bridges and exhibiting genuine 3D connectivity (Fig. S5b \ddagger), characterized by much lower volume. Importantly, the most stable LP polymorph is computed to be +6.7 kJ mol^{-1} uphill in energy with respect to substrates:



Thus, if prepared, this ternary fluoride might be only metastable. However, its kinetic stability with respect to phase separation is indicated by our phonons calculations, yielding no imaginary frequencies for this polymorph (Appendix S4 \ddagger , the same is true for all structures examined in this work).

High pressures. In the case of AgCuF_4 system, the LP layered $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$ structure is predicted to transform to a high-pressure $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$ polymorph (Fig. 3b, denoted HP1) with three-dimensional connectivity. The phase transition to the HP1

Table 1 Key geometry parameters of structures of parent AgF_2 and ternary silver fluorides $\text{Ag}^{\text{II}}\text{M}^{\text{II}}\text{F}_4$ ($M = \text{Cu}, \text{Ni}, \text{Cu}$) at ambient and increased pressure. Also, octahedral distortion parameter R is provided. N.D. stands for 'not determined' which is due to strong rhombic distortion

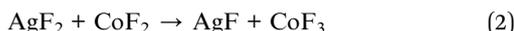
System	Label	p (GPa)	Bond length (Å)				R	Bond length (Å)			R
			Ag–F ₁	Ag–F ₂	Ag–F ₃	M–F ₁		M–F ₂	M–F ₃		
$\text{Ag}^{\text{II}}\text{F}_2$	LP	0	2.07	2.08	2.56	1.23	—	—	—	—	
	HP1	10	2.06	2.06	2.37	1.15	—	—	—	—	
$\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$	LP	0	2.05	2.07	2.60	1.26	1.92	1.92	2.19	1.14	
	HP1	10	2.03	2.10	2.38	1.15	1.85	1.91	2.15	1.14	
$\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$	LP	0	2.02	2.26	2.33	0.88	1.94	1.99	2.01	0.97	
	HP1	10	2.02	2.11	2.43	1.18	1.93	1.94	1.95	0.99	
$\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$	LP	0	2.03	2.27	2.33	0.88	1.98	2.03	2.03	0.98	
	HP1	10	2.01	2.18	2.33	N.D.	1.92	2.00	2.03	0.95	



from separate antiferromagnetic layers of $[\text{AgF}_{4/2}]$ and $[\text{NiF}_{4/2}]$ parallel to bc plane.

Cobalt

Ambient pressure. Interestingly, in the case of AgCoF_4 , the difference between standard reduction potentials for the $\text{Co}^{3+/2+}$ and $\text{Ag}^{2+/1+}$ redox pairs is considerable (1.82 V vs. 1.98 V,⁴⁴ respectively), so a reaction:



could be expected. Calculations show that this reaction between binary fluorides would not be favoured though, on both DFT+U level of theory (+25.8 kJ mol⁻¹) or hybrid density functional HSE06 (+12.2 kJ mol⁻¹, see HSE06 results for all the binary and ternary compounds in ESI, Table S2†). Having learned that, we tried to stabilize the $\text{Ag}^{\text{I}}\text{Co}^{\text{II}}\text{F}_4$ solution. This $\text{Ag}^{\text{I}}\text{Co}^{\text{II}}\text{F}_4$ LP polymorph (Fig. 2d) is isostructural with the lowest-energy $\text{Ag}^{\text{I}}\text{Ni}^{\text{II}}\text{F}_4$ LP structure. It exhibits the same inverse Jahn-Teller distortion pattern as the one described above in $\text{Ag}^{\text{I}}\text{Ni}^{\text{II}}\text{F}_4$ structure, *i.e.* substantial axial compression of $\text{Ag}(\text{I})$ sites and much smaller distortion at $\text{Co}(\text{II})$ sites, indicating that their half-filled orbitals are directed towards each other. This, together with a sufficiently large Ag-F-Co angle results in an antiferromagnetic ground state which, however, is at +5.7 kJ mol⁻¹ above binary divalent substrates.

Importantly, it appears that the lowest-energy mixed-cation structure obtained in the cobalt system corresponds to the $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ formulation, for which we also found the lowest-energy $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ polymorph. Structure quests using evolutionary algorithms resulted in many similar layered $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ structures, including KFeF_4 -HT polymorph ($Z = 4$, for others, see ESI, Fig. S1 and S2†). Further modifications helped us finding the lowest-energy $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ LP polymorph in the KFeF_4 -LT⁴⁵ type structure ($Z = 8$, Fig. 4a). DFT+U calculations yield the energy of this structure to be -4.2 kJ mol⁻¹ (or -24.8 kJ mol⁻¹ at HSE06 level) with respect to the binary divalent metal fluorides. It also turns out that the energy for the Lewis acid-Lewis base reaction:



is negative, about -34.8 kJ mol⁻¹ at DFT+U level (-37.4 kJ mol⁻¹ at HSE06 level, Table S2†), and it compensates for the unfavourable energy of the redox reaction (eqn (2)). Even for the models derived from parent AgF_2 type structure suitable to host $\text{Ag}(\text{II})$, the spontaneous electron-transfer reaction takes place; it manifests itself by the disappearance of the spin on Ag site and change of magnetic moment on the Co site. The reaction described by eqn (3) has a close analogue for other stoichiometry; the known cryolite type Ag_3CoF_6 contains no $\text{Ag}(\text{II})$, and its formula may be written as $\text{Ag}_3^{\text{I}}\text{Co}^{\text{III}}\text{F}_6$.

The KFeF_4 -LT type structure comprises the puckered antiferromagnetic anionic sheets of $[\text{CoF}_{4/2}\text{F}_{2/1}]^-$ stoichiometry which features high-spin $\text{Co}(\text{III})$ cations, and diamagnetic $\text{Ag}(\text{I})$ counterions. While in parent CoF_3 the octahedra are almost perfectly symmetric (with all bond lengths of 1.89 Å, the F-Co-F

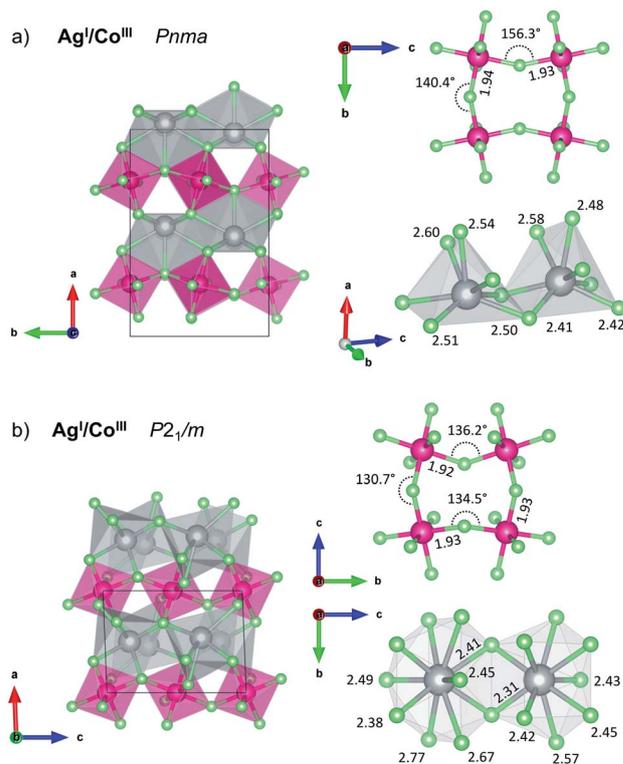


Fig. 4 Structure of $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ at (a) ambient and (b) elevated pressure (10 GPa), with selected geometric parameters of $\text{Ag}(\text{I})$ coordination polyhedra and $[\text{CoF}_{4/2}\text{F}_{2/1}]$ sheets. The threshold for Ag-F bond drawing is 2.7 Å in $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ structures.

angles are distorted $\pm 1.5^\circ$ from 90°), in $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ the CoF_6 octahedra are markedly compressed with axial bond length 1.82 Å resulting in R ratio equal 0.94 (equatorial bonds are highlighted on Fig. 4a). Considering the coordination sphere of $\text{Ag}(\text{I})$, pristine AgF crystallizes in rock-salt structure with regular octahedra having 2.426 Å Ag-F bond lengths. In the case of AgCoF_4 , however, two types of $\text{Ag}(\text{I})$ can be distinguished, each with coordination number, $\text{CN} = 7$ within 2.65 Å radius, and both in the form of a bicapped tetragonal pyramid.

High pressures. Comparing to Ni and Cu systems, richer polymorphism is predicted under elevated pressures in the AgCoF_4 system. The $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ solution gains stability at elevated pressures, forming the HP1 polymorph, which resembles the HP1 polymorph of AgCuF_4 described above (Fig. 3d). $\text{Ag}(\text{II})$ sites in $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ HP1 are far more axially compressed, suggesting a d-hole occupation mainly of d_{z^2} orbital oriented towards $\text{Co}(\text{II})$ sites. The Ag-F-Co bridges with 131° angle form chains leading to an antiferromagnetic ground state. The HP1 is favoured over LP polymorph above 5 GPa, but it would not be stabilized under high pressure like Ni and Cu systems. The relative enthalpy of $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ HP1 with respect to the parent divalent fluorides reaches a local minimum at about 9–10 GPa with +3.2 kJ mol⁻¹ (Fig. 1c, green series).

Likewise, at ambient pressure conditions, the intrinsic redox reaction in AgCoF_4 system is favoured at elevated pressures. Here the lowest-energy mixed valence LP $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ is predicted to undergo two subsequent high-pressure transitions at about



1 GPa (HP1) and 15 GPa (HP2), respectively while maintaining the metal oxidation states (Fig. 1c, magenta series). Both, HP1 and HP2 forms represent KMnF_4 type structures similarly as the LP one but with reduced symmetry according to the sequence $Pmna$ (LP) $\rightarrow P2_1/m$ (HP1) $\rightarrow C2/c$ (HP2). Apparently, it turns out that $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ stability would increase under high pressure about threefold with respect to substrates at 10 GPa, up to $-12.6 \text{ kJ mol}^{-1}$.

The first $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ high-pressure polymorph HP1 was found at 10 GPa using EA has a distorted monoclinic KMnF_4 type structure (Fig. 4b). This polymorph of $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ resembles the LP polymorph having antiferromagnetic puckered sheets of $[\text{CoF}_{4/2}\text{F}_{2/1}]^-$ stoichiometry with high-spin $\text{Co}(\text{III})$ cations and diamagnetic $\text{Ag}(\text{I})$ in between. Volume decrease of $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ with respect to binary fluorides is mainly due to enhancement of $[\text{CoF}_{4/2}\text{F}_{2/1}]^-$ layers buckling and increase of $\text{Ag}(\text{I})$ coordination number. Antiferromagnetic sheets are built from CoF_6 octahedra exhibiting axial bond compression with R ratio equal 0.92 (axial bonds are 1.78 Å, equatorial 1.92–1.93 Å, cf. Fig. 4b). The equatorial $\text{Co}-\text{F}$ bonds form a layer parallel to the bc plane. The $\text{Ag}(\text{I})$ cation is found at 10 GPa in two distinct crystallographic sites which differ in their coordination number. Here, CN is either 9 or 10, with bond lengths varying from 2.31 up to 2.77 Å. For comparison, at the same pressure, parent AgF is found in the CsCl type structure with cubic coordination sphere (8 ligands) and $\text{Ag}-\text{F}$ bond length of 2.47 Å. The second high pressure polymorph of $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ also crystallizes in KMnF_4 type structure ($C2/c$). It features higher CN for $\text{Ag}(\text{I})$ sites and more buckled $[\text{CoF}_{4/2}\text{F}_{2/1}]^-$ layers.

Electronic properties

The main motivation behind studying novel ternary $\text{Ag}(\text{II})$ fluorides is to achieve appreciable changes in electronic structure that would result in facile metallization within the $[\text{AgF}_2]$ layers either at ambient or elevated pressures. To evaluate this possibility, we first discuss the electronic density of states (DOS) computed for AgF_2 and the studied ternary AgMF_4 fluorides at DFT+U level and zero pressure. Subsequently, we discuss the impact of pressure on their bandgaps.

Ambient pressure. The total and orbital-projected electronic DOS plots at ambient pressure are shown in Fig. 5. The DOS of the parent AgF_2 (Fig. 5a) shows a narrow band gap (1.33 eV) with a strong mixture of Ag 4d and F 2p orbitals around the Fermi level, with the Ag states dominate the lower-energy valence DOS and F states dominate the higher-energy valence DOS.^{1,30} The gap opens between valence bands of predominantly F character and conduction bands of predominantly Ag character. The lowest-energy conduction band (centred around 1.5 eV) and the lowest-energy valence band (~ -6.5 eV) represent the upper and lower Hubbard band (UHB and LHB; marked with red arrows in Fig. 5) of dominant Ag $d_{x^2-y^2}$ character, respectively. The large separation of these bands on the energy scale and their position relative to F states define AgF_2 as a charge-transfer (CT) insulator according to the Zaanen–Sawatzky–Allen classification scheme.⁴⁶

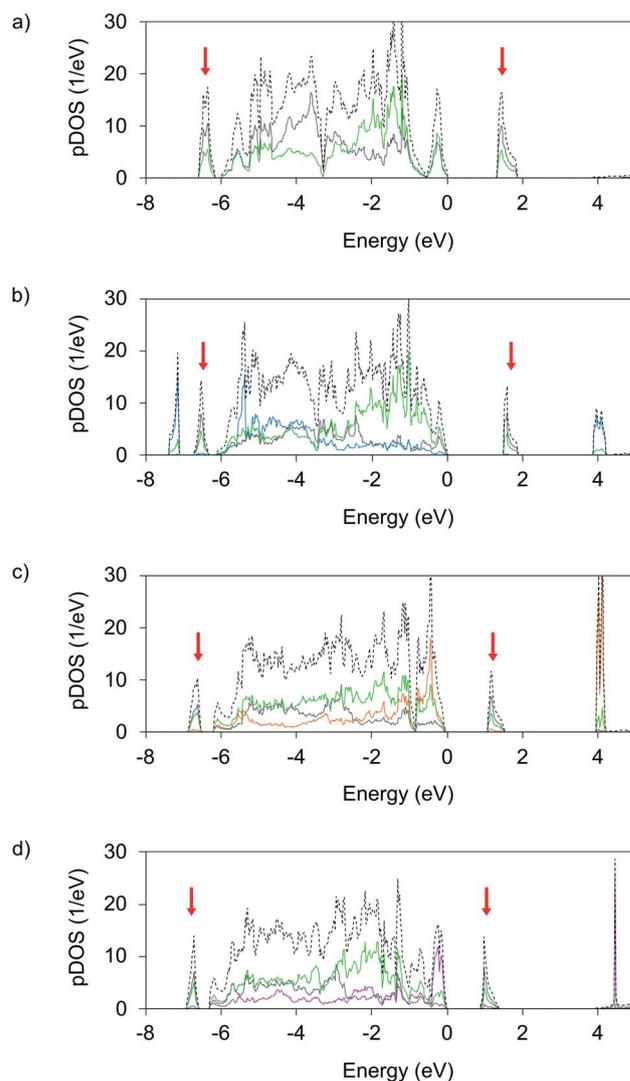


Fig. 5 Orbital projected electronic density of states (pDOS) calculated on DFT+U level for (a) parent AgF_2 , (b) $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$, (c) $\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$, and (d) $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ compounds at 0 GPa. Red arrows indicate lower and upper Hubbard (LHB and UHB) bands of Ag^{2+} . Dashed lines indicate total DOS, Ag states are drawn in grey, F in green, Cu in blue, Ni in orange and Co in magenta. Fermi level is set to zero. Spin-up and spin-down states were summed up.

Analysis of the LP $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$ electronic DOS (Fig. 5b) shows that the formation of this compound does not lead to significant electronic changes within the $[\text{AgF}_{4/2}]$ layers with respect to pristine AgF_2 . The main difference is the presence of Cu 3d states. The Cu valence states show similar distribution as the valence Ag states, while the LHB (~ 7.5 eV) and UHB (~ 4 eV) of Cu display even larger separation than the Ag ones, which reflects the larger U at $\text{Cu}(\text{II})$ sites. Consequently, the nature of the bandgap of AgCuF_4 is defined by the bandgap of the $[\text{AgF}_{4/2}]$ sublayer. It is only slightly broader than in the parent AgF_2 (1.46 eV vs. 1.33 eV). Evidently, both the $[\text{AgF}_{4/2}]$ and $[\text{CuF}_{4/2}]$ layers in AgCuF_4 are well electronically separated, preserving the nature of their respective substrates, *i.e.* insulating character associated with a ligand to metal CT gap.



More significant changes *vs.* AgF_2 are observed in the DOS for AgNiF_4 (Fig. 5c). Here, the additional Ni 3d states predominate the valence DOS at the highest energies below the Fermi level and on average above the F 2p valence states. This contrasts AgF_2 and AgCuF_4 DOS, where the metal states are on average shifted to lower energies relative to F 2p valence states. Due to the appearance of the Ni states at higher energies the position of the Ni LHB is positioned just below the Fermi level, while the conduction band preserves the character of the Ag UHB band level. This means that the CT character of the bandgap has changed. Now the charge transfer is realized between the valence states of dominant Ni and conduction states of dominant Ag character. The appearance of Ni 3d states above the F 2p states of valence DOS results in a noticeably narrower band gap (1.09 eV) than in parent AgF_2 (1.33 eV).

In the case of $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$, the Co 3d (Fig. 5d) valence states are shifted to even higher energies relative to the F 2p valence resulting in an even narrower bandgap of 0.90 eV. The Co LHB positioned just below the Fermi level has almost the entire Co character, meaning that charge transfer over the bandgap is now from Co(II) states to the UHB of Ag(II), and indicate the proximity of intrinsic redox reaction character.

Noticeably, the band gaps of $\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$ and $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ have an intervalence CT character, with Ni(II)/Co(II) serving as an electron donor, and Ag(II) as an acceptor, the intervalence CT being more pronounced in $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$. The picture of $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ is reversed relative to both $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ and $\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$, here the top of the valence band mainly consists of filled 4d states of Ag(I) while the bottom of the conduction band corresponds to the UHB of Co(III) (Fig. S7a†). Due to the intrinsic redox reaction discussed above band gap increases up to 2.02 eV, it is thus larger than that of AgF_2 , and of the $\text{Ag}^{\text{II}}\text{M}^{\text{II}}\text{F}_4$ analogues.

Clearly, the electronic structure of AgMF_4 compounds in the series $\text{M} = \text{Cu}, \text{Ni}, \text{Co}$, changes together with the redox properties of M(II) cations. The gradual change of M bands contribution to the valence band is apparent on band structure plots, Fig. S8,† as well as in DOS (Fig. 5). For AgCuF_4 , with Cu(III) in fluoride environment is experimentally accessible with the greatest difficulty, AgCuF_4 preserves Ag(II) and Cu(II) oxidation

states and a ligand to metal CT insulator character. For AgNiF_4 , where Ni(III) forms easier, electronic DOS reveals moderate ease of intervalence CT between Ni(II) donor and Ag(II) acceptor, with the corresponding valence and conduction bands separated by a mere ~ 1.1 eV. Finally, for $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$, where Co(III) is most accessible, a genuine redox reaction is seen which leads to “inverse” intervalence CT character, where Ag(I) serves as an electron donor, while Co(III) as an acceptor. Note that our hybrid DFT (HSE06) calculations yielded qualitatively similar results for the ambient pressure AgMF_4 structures (Fig. S9†).

Increased pressures. Fig. 6 shows the evolution of the bandgap with pressure in all modelled AgMF_4 systems. The band gap of $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$ remains almost constant about 1.5 eV up to 20 GPa, while experiencing only a slight increase upon the LP \rightarrow HP1 phase transition at ~ 6 GPa. Interestingly in $\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$ the LP \rightarrow HP1 transition at ~ 3 GPa is accompanied by severe reduction of the band gap by a factor of two from ~ 1.1 to ~ 0.6 eV. After the transition, however, the band gap remains almost unchanged up to 20 GPa, excluding the prospect of its metallization. These features suggest the intervalence CT character of AgNiF_4 and a certain propensity towards redox process yielding higher oxidation states of Ni, with a concomitant reduction of Ag(II) to Ag(I). On the other hand, band gap of $\text{Ag}^{\text{II}}\text{Co}^{\text{II}}\text{F}_4$ decreases monotonically throughout the entire pressure range, but its reduction is nevertheless small, and the band gap equals ~ 0.7 eV at 20 GPa, so the pressure does not provide an opportunity for its metallization below 20 GPa either. The picture of $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$ is the opposite, its bandgap is increased with every phase transition after which it only slowly monotonically decreases. Consequently, the bandgap at 20 GPa is even slightly higher (2.1 eV) than the 0 GPa value of 2.0 eV.

Conclusions

The silver(II) fluoride system is theoretically predicted to resist forming ternary fluorides with Cu, and Ni fluorides at ambient pressure conditions. The isostructural substitution is largely unfavoured at ambient pressure due to excessive differences in Ag(II) and M(II) bond lengths and in the extent of their tetragonal distortion. The energies of formation of $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$ and

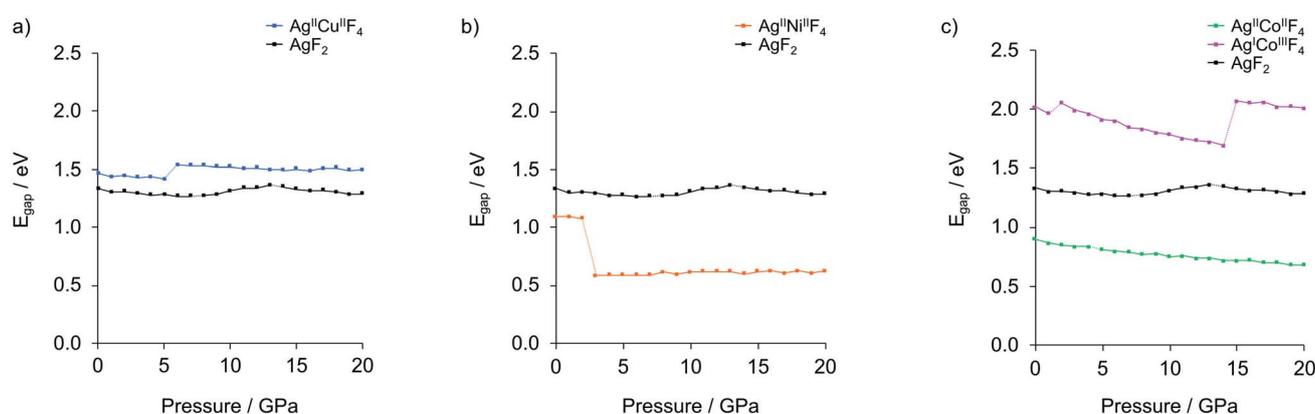


Fig. 6 Electronic band gaps dependency on pressure elevation for the lowest-enthalpy structures of (a) AgCuF_4 , (b) AgNiF_4 and (c) AgCoF_4 (shown together with AgF_2). Dotted lines connect values calculated for structures separated by phase transitions. Detailed data is provided in Table S3.†



$\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$ are positive but these compounds have real phonon frequencies, hence could be metastable if prepared. Both $\text{Ag}^{\text{II}}\text{Cu}^{\text{II}}\text{F}_4$ and $\text{Ag}^{\text{II}}\text{Ni}^{\text{II}}\text{F}_4$ are predicted to be semiconductors with a predominant charge-transfer character. There is a clear trend in electronic band gaps and character of the states at the top of the valence band as one moves from Cu, *via* Ni to Co. The AgCuF_4 system has a comparable band gap with that of pristine AgF_2 at ambient pressure (1.46 eV *vs.* 1.33 eV), while AgNiF_4 system features a narrower band gap (1.09 eV).

The cobalt(II) system displays many similarities to both nickel and copper structures while having an even smaller band gap (0.90 eV). However, $\text{Ag}^{\text{II}}\text{Co}^{\text{III}}\text{F}_4$ configuration is predicted to be energetically unstable due to the potent oxidizing properties of Ag^{II} . The cobalt–silver fluoride system is thus quite different from the other two due to the intrinsic redox process resulting in a preference for as yet unknown $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$. The ambient-pressure KFeF_4 type structure of this species is computed to be a *ca.* 2.02 eV band gap semiconductor, stable with respect to binaries and featuring antiferromagnetic sheets of $[\text{CoF}_{4/2}\text{F}_{2/1}]$ stoichiometry.

Application of hydrostatic pressure *in silico* shows that there is a pressure range where the formation of ternary silver fluorides AgMF_4 is favoured over binaries. The calculated range of stability is about 7–15 GPa for AgCuF_4 , 8–15 GPa for AgNiF_4 , and 0–22 GPa for $\text{Ag}^{\text{I}}\text{Co}^{\text{III}}\text{F}_4$, meaning that in these conditions each system has a negative enthalpy of formation with respect to substrates. The nickel system appears to be interesting in terms of electronic structure because at 10 GPa it should form the separate layers polymorph with a narrow band gap of about 0.62 eV, less than half of that for AgF_2 . Regrettably, none of the system studied would be metallic or would feature electronically doped AgF_2 sheets. The Co system is overdoped in that sense that Ag^{II} becomes entirely reduced to Ag^{I} . Thus, doping to AgF_2 remains a daunting target for the future studies.

Importantly, our study shows that in ternary fluorides of Ag and M (M = Ni, Cu), the $\text{Ag}^{\text{I}}\text{M}^{\text{III}}\text{F}_4$ formulation is not stable with respect to $\text{Ag}^{\text{II}}\text{M}^{\text{II}}\text{F}_4$, unlike in the known ternary oxides of these metals, AgMO_2 . Thus, Cu(II) and Ni(II) are expected to resist oxidizing power of Ag^{II} both at ambient and elevated pressures while in the fluoride environment. Compounds with a formula $\text{Ag}^{\text{II}}\text{M}^{\text{II}}\text{F}_4$ might hold strong antiferromagnetic interactions due to the presence of strong spin-polarizer Ag^{II} and second magnetic cation of 3d series. Scrutiny of the strength of magnetic interactions in these systems, especially a detailed description of superexchange coupling between Ag^{II} and M(II) spins, will be performed in a forthcoming study.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- J. Gawraczyński, D. Kurzydłowski, R. A. Ewings, S. Bandaru, W. Gadomski, Z. Mazej, G. Ruani, I. Bergenti, T. Jaroń, A. Ozarowski, S. Hill, P. J. Leszczyński, K. Tokár, M. Derzsi, P. Barone, K. Wohlfeld, J. Lorenzana and W. Grochala, *Proc. Natl. Acad. Sci. U. S. A.*, 2019, **116**, 1495–1500.
- D. Kurzydłowski, M. Derzsi, P. Barone, A. Grzelak, V. Struzhkin, J. Lorenzana and W. Grochala, *Chem. Commun.*, 2018, **54**, 10252–10255.
- W. Grochala and R. Hoffmann, *Angew. Chem., Int. Ed.*, 2001, **40**, 2742–2781.
- W. Grochala and Z. Mazej, *Philos. Trans. R. Soc., A*, 2015, **373**, 20140179.
- A. Grzelak, M. Derzsi and W. Grochala, *Inorg. Chem.*, 2021, **60**, 1561–1570.
- S. Bandaru, M. Derzsi, A. Grzelak, J. Lorenzana and W. Grochala, *Phys. Rev. Mater.*, 2021, **5**, 064801.
- R. Hoppe and G. Siebert, *Z. Anorg. Allg. Chem.*, 1970, **376**, 261–267.
- G. Stebert and R. Hoppe, *Naturwissenschaften*, 1971, **58**, 95–96.
- C. Shen, L. C. Chacón, N. Rosov, S. H. Elder, J. C. Allman and N. Bartlett, *C. R. Acad. Sci., Ser. IIc: Chim.*, 1999, **2**, 557–563.
- N. Bartlett, G. Lucier, C. Shen, W. J. Casteel, L. Chacon, J. Munzenberg and B. Žemva, *J. Fluorine Chem.*, 1995, **71**, 163–164.
- B. Žemva, K. Lutar, A. Jesih, W. J. Casteel, A. P. Wilkinson, D. E. Cox, R. B. Von Dreele, H. Borrmann and N. Bartlett, *J. Am. Chem. Soc.*, 1991, **113**, 4192–4198.
- J. Grannec, A. Yacoubi, A. Tressaud and L. Rabardel, *Solid State Commun.*, 1988, **68**, 363–367.
- J. Curda, W. Klein, H. Liu and M. Jansen, *J. Alloys Compd.*, 2002, **338**, 99–103.
- Y. J. Shin, J. P. Doumerc, P. Dordor, C. Delmas, M. Pouchard and P. Hagenmuller, *J. Solid State Chem.*, 1993, **107**, 303–313.
- T. Sörgel and M. Jansen, *Z. Anorg. Allg. Chem.*, 2005, **631**, 2970–2972.
- W. Stählin and H.-R. Oswald, *Z. Anorg. Allg. Chem.*, 1969, **367**, 206–208.
- H. Muguerra, C. Colin, M. Anne, M.-H. Julien and P. Strobel, *J. Solid State Chem.*, 2008, **181**, 2883–2888.
- M. Al-Mamouri, P. P. Edwards, C. Greaves and M. Slaski, *Nature*, 1994, **369**, 382–384.
- W. Grochala, R. Hoffmann, J. Feng and N. W. Ashcroft, *Angew. Chem., Int. Ed.*, 2007, **46**, 3620–3642.
- Y. Liu-Xiang, Z. Jing-Geng, Y. Yong, L. Feng-Ying, Y. Ri-Cheng and J. Chang-Qing, *Chin. Phys. Lett.*, 2006, **23**, 426–427.
- A. Grzelak, J. Gawraczyński, T. Jaroń, D. Kurzydłowski, A. Budzianowski, Z. Mazej, P. J. Leszczyński,



- V. B. Prakapenka, M. Derzsi, V. V. Struzhkin and W. Grochala, *Inorg. Chem.*, 2017, **56**, 14651–14661.
- 22 G. Kresse and J. Hafner, *J. Phys.: Condens. Matter*, 1994, **6**, 8245–8257.
- 23 G. Kresse and J. Furthmüller, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1996, **54**, 11169–11186.
- 24 G. Kresse and D. Joubert, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1999, **59**, 1758–1775.
- 25 J. P. Perdew, A. Ruzsinszky, G. I. Csonka, O. A. Vydrov, G. E. Scuseria, L. A. Constantin, X. Zhou and K. Burke, *Phys. Rev. Lett.*, 2008, **100**, 136406.
- 26 A. I. Liechtenstein, V. I. Anisimov and J. Zaanen, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1995, **52**, R5467–R5470.
- 27 S. L. Dudarev, G. A. Botton, S. Y. Savrasov, C. J. Humphreys and A. P. Sutton, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1998, **57**, 1505–1509.
- 28 J. A. Barreda-Argüeso, S. López-Moreno, M. N. Sanz-Ortiz, F. Aguado, R. Valiente, J. González, F. Rodríguez, A. H. Romero, A. Muñoz, L. Nataf and F. Baudelet, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2013, **88**, 214108.
- 29 M. Cococcioni and S. de Gironcoli, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2005, **71**, 035105.
- 30 C. Miller and A. S. Botana, *Phys. Rev. B*, 2020, **101**, 195116.
- 31 D. Kurzydłowski, *Crystals*, 2018, **8**, 140.
- 32 L. C. Ming, M. H. Manghnani, T. Matsui and J. C. Jamieson, *Phys. Earth Planet. Inter.*, 1980, **23**, 276–285.
- 33 D. C. Lonie and E. Zurek, *Comput. Phys. Commun.*, 2011, **182**, 372–387.
- 34 *XtalOpt – Publications*, <http://xtalopt.github.io/pub.html>, accessed October 2, 2020.
- 35 A. V. Krukau, O. A. Vydrov, A. F. Izmaylov and G. E. Scuseria, *J. Chem. Phys.*, 2006, **125**, 224106.
- 36 K. Momma and F. Izumi, *J. Appl. Crystallogr.*, 2011, **44**, 1272–1276.
- 37 U. Herath, P. Tavadze, X. He, E. Bousquet, S. Singh, F. Muñoz and A. H. Romero, *Comput. Phys. Commun.*, 2020, **251**, 107080.
- 38 W. Setyawan and S. Curtarolo, *Comput. Mater. Sci.*, 2010, **49**, 299–312.
- 39 P. Fischer, D. Schwarzenbach and H. M. Rietveld, *J. Phys. Chem. Solids*, 1971, **32**, 543–550.
- 40 W. Massa and D. Babel, *Chem. Rev.*, 1988, **88**, 275–296.
- 41 B. Žemva, K. Lutar, L. Chacon, M. Fele-Beuermann, J. Allman, C. Shen and N. Bartlett, *J. Am. Chem. Soc.*, 1995, **117**, 10025–10034.
- 42 W. Grochala, *Phys. Status Solidi B*, 2006, **243**, R81–R83.
- 43 In fact, during standard geometry optimization process a smooth transition between both HP1 and LP polymorphs occurred (*i.e.* optimization of HP1 polymorph at 0 GPa gave LP structure and also optimization of LP polymorph at 10 GPa led to HP1 structure).
- 44 A. J. Bard, R. Parsons, J. Jordan and International Union of Pure and Applied Chemistry, *Standard potentials in aqueous solution*, M. Dekker, New York, 1985.
- 45 J. Lapasset, P. Sciau, J. Moret and N. Gros, *Acta Crystallogr., Sect. B: Struct. Sci.*, 1986, **42**, 258–262.
- 46 J. Zaanen, G. A. Sawatzky and J. W. Allen, *Phys. Rev. Lett.*, 1985, **55**, 418–421.

