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## Octahedral tilting in Prussian blue analogues†

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Octahedral tilting is key to the structure and functionality of perovskites. We present a metastudy of published literature showing how these distortions manifest in the related Prussian blue analogues (PBAs): cyanide versions of double perovskites with formula  $AM[M'(CN)_6]_{1-y}\square_y \cdot nH_2O$  ( $A$  = alkali metal,  $M$  and  $M'$  = transition metals,  $\square$  = vacancy/defect). Tilts are favoured by high values of  $x$  if  $A = Na$  or  $K$ , whereas the transition metals play a less important role. External hydrostatic pressure induces tilt transitions nearly irrespective of the stoichiometry, whereas thermal transitions are only reported for  $x > 1$ . Interstitial water can alter the transitions induced by a different stimulus, but (de)hydration *per se* does not lead to tilts. Finally, the implications for rational design of critical functionality—including improper ferroelectricity and electrochemical performance—are discussed. The results are integral for a fundamental understanding of phase transitions and for the development of functional materials based on PBAs.

## 1 Introduction

Prussian blue analogues (PBAs) are a versatile class of materials with a wide range of potential applications. The functional diversity partially arises from the large scope for compositional

variation: the general formula is  $A_xM[M'(CN)_6]_{1-y}\square_y \cdot nH_2O$ , where  $A$  is an alkali metal,  $M$  and  $M'$  are normally transition metals and  $\square$  denotes a vacancy. Porous, defective systems of formula  $M^{II}[M^{III}(CN)_6]_{0.67}$  can be used for catalysis and adsorption of gases and toxic metals,<sup>1,2</sup> whereas defect-free, alkali-containing PBAs, *e.g.*  $A_2M^{II}M^{III}(CN)_6$ , are suitable electrode materials<sup>3</sup> and/or may show interesting magnetic properties.<sup>4</sup> The stoichiometry and associated functionality is stipulated by the charges of the transition metals, where lower charges increase the scope for inclusion of vacancies and/or A-site cations [Fig. 1]. The crystal structure of PBAs is reminiscent of that of double perovskites with two octahedrally coordinated

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of Prof. Bettina Lotsch. Hanna's research interests revolve around the crystallography of metal–cyanide frameworks, often under nonambient conditions, and she has a particular soft spot for complexes containing the beautiful blue  $Cu^{2+}$  ion.

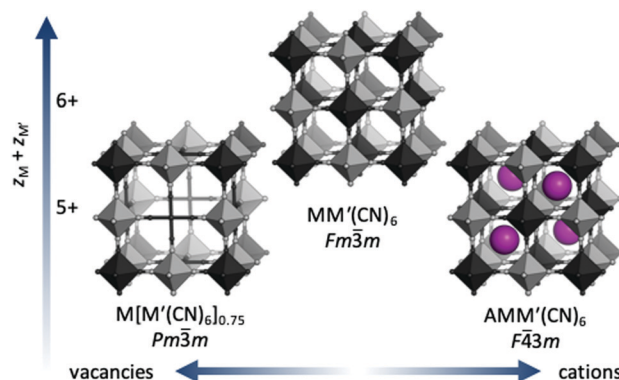


Fig. 1 The crystal structure of Prussian blue analogues. If the charges of the transition metals ( $z_M + z_{M'}$ ) sum to 6, the ordered  $MM'(CN)_6$  is formed. For lower charges, vacancies or A-site cations are included to give the formulae  $M[M'(CN)_6]_{y < 1}$  and  $A_{x > 0}M[M'(CN)_6]$ , respectively.  $M$  is shown in dark grey,  $M'$  in light grey and  $A$  in purple.



metals:  $M(\text{NC})_6$  and  $M'(\text{CN})_6$ . The parent structure (aristotype) adopts the space group  $Fm\bar{3}m$ , although ordered A-site cations or vacancies may reduce the symmetry to  $F\bar{4}3m$  or  $Pm\bar{3}m$  [Fig. 1].

A crucial feature of  $\text{ABX}_3$  perovskite physics is octahedral tilting, which involves in-phase or out-of-phase rotation of  $\text{BX}_6$  octahedra. In Glazer notation, this is denoted by superscripted '+' and '-' and lowercase letters indicate relative magnitudes around the three pseudo-cubic axes.<sup>5</sup> The importance of tilts arises from their link to both the composition and to the properties. For example, the relative ionic radii of the constituent metals, as expressed by the tolerance factor,<sup>6</sup> dictate whether tilts are favoured, which facilitates some degree of control. Compositional modification can be used to tune the tilt angle, which in turn affects *e.g.* the band gap and the Curie temperature.<sup>7</sup> Moreover, the link between tilting and structure is well established *via* group-theoretical methods,<sup>8,9</sup> and knowledge of the tilts typically allows for the prediction of the space group symmetry. This was exploited in so-called tilt engineering of a multiferroic perovskite derivative, where careful activation of appropriate tilts led to polar symmetry with coexisting weak magnetism.<sup>10</sup> Octahedral tilts therefore present an attractive route for the design of technologically relevant materials.

Given the structural similarities between perovskites and PBAs, it is natural that octahedral tilting also occurs in PBAs with functional implications. By way of example, the tilts in  $\text{Na}_2\text{MnMn}(\text{CN})_6$  nearly triple the magnetic transition temperature compared to the untilted  $\text{Cs}_2\text{MnMn}(\text{CN})_6$ .<sup>11</sup> A less favourable situation is the drastic volume reduction of 17% in  $\text{Mn}[\text{Mn}(\text{CN})_6]_{0.93}$  upon Na intercalation, which is driven by a tilt transition from cubic symmetry (*i.e.* untilted) to  $a^-a^-a^-$ .<sup>12</sup> This has a detrimental effect on the electrode stability and compromises the application of PBAs as energy storage materials. As a consequence, understanding and ultimately controlling the presence or absence of octahedral tilts in PBAs is key to their commercial development as functional materials.

In spite of its importance, octahedral tilting in PBAs is poorly understood and there is considerable confusion regarding the structural characterisation of these materials. To illustrate, cubic (no tilts) and monoclinic symmetries ( $a^-a^-b^+$  tilts) were postulated for the closely related  $\text{Na}_{1.52}\text{Ni}[\text{Fe}(\text{CN})_6]_{0.88}$  and  $\text{Na}_{1.48}\text{Ni}[\text{Fe}(\text{CN})_6]_{0.89}$ , respectively,<sup>13,14</sup> while a third study claims  $\text{Na}_x\text{Ni}[\text{Fe}(\text{CN})_6]_{0.83}$  to be rhombohedral ( $a^-a^-a^-$  tilts) at all  $x$ -values.<sup>15</sup> A systematic understanding of the factors underlying octahedral tilting in PBAs would be beneficial to a wide range of fields and pave the way for tilt engineering approaches. Certain principles developed for inorganic perovskites are likely transferable to PBAs, which provides a starting point for such investigations. However, PBAs show features that are rare or unknown in perovskites, such as vacancies and porosity, and therefore their behaviour cannot be expected to exactly mirror that of perovskites.

Here, we perform a metastudy to investigate the octahedral tilting in Prussian blue analogues. Our manuscript identifies the possible driving forces for tilting—stoichiometry, composition, hydration, and nonambient conditions—and discusses their effect on the propensity for, and nature of, tilting. The results

are compared and contrasted with the tilt behaviour of double perovskites throughout. Our results show that tilts are favoured by high A-site cation concentrations if  $A = \text{Na}$  or  $\text{K}$ , whereas the identity of the transition metals is considerably less relevant. The presence of interstitial water can direct the tilt transitions induced by a different stimulus, but (de)hydration does not appear to drive tilts in its own right. External hydrostatic pressure can induce tilt transitions almost regardless of the stoichiometry, whereas thermal transitions only occur for high A-site cation concentrations. We conclude by discussing strategies for tilt engineering, using energy storage, magnetism, and improper ferroelectricity as example functionalities.

## 2 Methods

A database of PBA structures was created manually by retrieving a large number of research articles (170 articles, 564 compounds) [ESI†]. The identities of the A, M, and M' sites,  $x$ - and  $y$ -values, and presence/absence of tilting were extracted. Only studies where the ambient structure was confirmed by diffraction and the composition characterised by either EDX or ICP were included. As Rietveld refinements are not routinely carried out, any deviation from cubic symmetry—manifested by reflection splitting—was considered to be due to tilting, except in cases where other symmetry-lowering distortion (*i.e.* Jahn–Teller distortions) are obviously present. As uncertainties from elemental analysis are rarely reported, no error bars were included in the figures and thus quantitative conclusions should be drawn with caution. Compounds with mixed cations on the A-site where the minority species exceeded 5% of the total  $x$ -value were excluded from Fig. 2, although it should be stressed that many PBAs contain a small amount of  $\text{K}^+$  from the synthesis. Likewise, systems with mixed M-site metals were not included in Fig. 4.

## 3 Results

### 3.1 Stoichiometry

As mentioned, PBAs have a variable stoichiometry described by the general formula  $\text{A}_x\text{M}[\text{M}'(\text{CN})_6]$  ( $\square = \text{vacancy}$ ). As A-site cations ( $x$ ) and vacancies ( $y$ ) often coexist, a continuum of intermediate stoichiometries is accessible. Fig. 2 depicts the compositional space in terms of  $x$  and  $y$ , populated by structures reported in literature. Lines corresponding to compositions  $\text{A}_x^{\text{I}}\text{M}^{\text{II}}[\text{M}'^{\text{III}}(\text{CN})_6]_{\frac{2+x}{3}}\square_{\frac{1-x}{3}}$  ( $0 \leq x \leq 1$ ) and  $\text{A}_x^{\text{I}}\text{M}^{\text{II}}[\text{M}'^{\text{II}}(\text{CN})_6]_{\frac{2+x}{4}}\square_{\frac{2-x}{4}}$  ( $0 \leq x \leq 2$ ) are indicated and many structures fall close to these lines. In particular, PBAs with redox-inactive transition metals will be found here. Entries in other areas of the phase diagram represent PBAs with mixed oxidation states of M and/or M', *e.g.*  $\text{K}_{0.4}\text{Cu}[\text{Fe}_{0.6}^{\text{II}}\text{Fe}_{0.4}^{\text{III}}(\text{CN})_6]_{2/3}$ .<sup>16</sup> This phase diagram highlights two common features of PBAs that rarely occur in double oxide perovskites: partially occupied A-sites, *e.g.*  $\text{AMM}'(\text{CN})_6$ , and  $\text{M}'(\text{CN})_6$  vacancies, *e.g.*  $\text{AM}[\text{M}'(\text{CN})_6]_{y < 1}$ .





**Fig. 2** Tilts in PBAs as a function of stoichiometry. Top panel: PBAs with composition  $A_xM[M'(CN)_6]_{1-y}\square_y$  ( $\square$  = vacancy) for various A, where filled (empty) symbols denote tilted (untilted) structures. The diagonal lines show compositions with a constant sum of the transition metal charges (+5 and +4). Representative structures are shown for key stoichiometries, with the M and M' ions in black and grey, respectively, and the A-site cation in purple. Cyanide ions are omitted for clarity. Lower panel: The above phase diagram plotted with a separate figure for each A-site cation.

Fig. 2 demonstrates that a minimum concentration of alkali metals is required for tilting. As uncertainties from elemental analyses are rarely reported, no error bars are included in Fig. 2, and hence it is difficult to draw compelling quantitative conclusion. Still, nearly all tilted PBAs show  $x > 1$ , suggesting that this is a necessary condition for tilts. Yet, it is not a sufficient condition, as several reportedly cubic PBAs with higher A-site concentrations exist.<sup>17,18</sup> While such discrepancies may partially stem from suboptimal data quality of in-house diffractometers or incorrect compositions, differences in local structure due to deviating synthesis conditions may also play a role. The relatively empty region at  $x = 1.0$ – $1.5$  and  $y = 0$ – $0.1$  in Fig. 2 suggests a miscibility gap, which agrees with the phase separation sometimes reported in PBAs with large values of  $x$ .<sup>12,19</sup> A detailed understanding of the critical threshold concentration and potential miscibility gap is crucial for the application of PBAs in secondary ion batteries, as the tilt transition changes the transport properties and causes an unwanted strain.<sup>12,14</sup> Consequently, further studies are needed, though it is clear that the A-site concentration is central to the tilts.

In principle, vacancies could affect the propensity for tilting by reducing the tilt correlation length, thereby preventing global phase transitions. The disorder of the vacancies is complex and depends both on the metal ions and the synthesis conditions,<sup>20</sup> which complicates the study of the functional implications of missing  $M'(CN)_6$  clusters. Moreover, as vacancies

and A-site cations are interdependent, their respective roles are difficult to decouple. However, the absence of vacancies is not sufficient to induce tilting as PBAs with formula  $MM'(CN)_6$  are invariably undistorted at ambient conditions.<sup>21</sup> Likewise, certain PBAs exhibit tilts despite a high vacancy concentration, like  $Na_{1.10}Mn[Fe(CN)_6]_{0.77}$ .<sup>22</sup> Thus, vacancies alone do not appear to play a major role in the tilting; however, this may be system-dependent and further studies are encouraged.

Finally, a few general comments can be made about Fig. 2. First, a considerable number of systems comprise transition metal ions with charges summing to less than 4 (area above the right diagonal line). This indicates a partially univalent transition metal or the presence of hydroxide ions in the framework.<sup>23,24</sup> Second, several structures feature an apparent vacancy content above 33% (top left corner). However, certain transition metal ions have been postulated to occupy both the A- and M-site, such as  $Cu[Fe(CN)_6]_{0.5}$ ,<sup>25</sup> which means that the actual vacancy concentration of such structures is less than 50%. While the possibility of divalent A-site cations and their relation to the maximum vacancy concentration is interesting and merits further study, this will not be discussed further in this manuscript.

### 3.2 A-site composition

The tendency for tilting not only depends on the concentration of A-site cations, but also on the A-site ionic radius [Fig. 2].



PBAs based on Na or K feature the largest proportions of tilted structures, whereas systems with A = Li rarely tilt. Although relatively understudied, some Rb-containing tilted structures are known,<sup>11,26,27</sup> e.g.  $\text{Rb}_2\text{MnMn}(\text{CN})_6$  ( $x \sim 2$ ). Due to the lack of elemental analysis, this compound is not included in Fig. 2.<sup>11</sup> To the best of our knowledge, distorted Cs-containing PBAs do not exist at ambient conditions. Experimental evidence additionally suggests that  $\text{Cs}^+$  may preferentially occupy the vacant sites in systems with  $M'$ -site vacancies,<sup>28,29</sup> which would further decrease the tendency for Cs to induce structural distortions. While some observational bias is present here—Na- and K-containing systems are the most intensely studied—intermediate alkali metal radii appear to favour tilting.

The correlation between A-site cation size and tilt propensity partially agrees with perovskites, where the driving force for tilts is considered to be the underbonding of small A-site cations, as quantified by the tolerance factor.<sup>6,30,31</sup> Although the tolerance factor has been extended to molecular perovskites,<sup>32</sup> it is less applicable as it does not account for vacancies. Yet, the same argument underlies the prevalence of tilting in PBAs with A = Na/K relative to A = Rb/Cs, as smaller cations are more prone to underbonding. It is also consistent with the inverse relationship between tilt angles and A-site cation size in  $\text{A}_2\text{MnMn}(\text{CN})_6$ .<sup>33</sup> It does not rationalise the lack of tilting in Li-based PBAs, but Li is believed to occupy the window sites of the PBA subcube, as opposed to the centre.<sup>34</sup> This mirrors the behaviour of Li-containing perovskites.<sup>35,36</sup> Thereby, the bonding environment can presumably be optimised even without tilts. Altogether, the radius of the A-site cation is a key factor to consider when evaluating the propensity for tilting of a given structure.

In general, the size of the A-site cation also stipulates the type of tilt [Fig. 3]. A-site deficient PBAs under compression preferentially adopt  $a^-a^-a^-$  tilts giving  $R\bar{3}$  symmetry,<sup>37</sup> which is also seen in the fluoride analogues  $\text{MnNbF}_6$  and  $\text{CaTiF}_6$ .<sup>38,39</sup> This tilt pattern is also preferred by dehydrated Na-containing PBAs<sup>11,40–42</sup> and allows the Na ion to displace along the cubic [111] direction towards one of the transition metals. This displacement is sometimes considered the driving force for cubic–rhombohedral phase transitions, which would give rhombohedral  $R\bar{3}m$  symmetry in the absence of tilts.<sup>43–45</sup> As the reflection conditions of  $R\bar{3}m$  and  $R\bar{3}$  are identical, distinguishing between these space groups is difficult. Yet, as framework distortions and A-site displacements are likely to couple, we believe structures reported in  $R\bar{3}m$  are possibly better described in  $R\bar{3}$  with  $a^-a^-a^-$  tilts in conjunction with A-site displacements. Similar situations have been noted for oxide perovskites.<sup>46</sup>

The  $a^-a^-b^+$  tilt pattern is the most prevalent in oxide perovskites and it is known for PBAs with A = Na, K, or Rb and large  $x$  values.<sup>11,46,47</sup> This tilt pattern drives monoclinic  $P2_1/n$  symmetry<sup>9</sup> and the A-site cation has three translational degrees of freedom, allowing a complete optimisation of the bonding environment.<sup>48</sup> In addition to PBAs with compositions close to the ideal  $\text{A}_2\text{MM}'(\text{CN})_6$ ,  $a^-a^-b^+$  tilts can also be induced by pressure in  $\text{Rb}_{0.87}\text{Mn}[\text{Co}(\text{CN})_6]_{0.91}$ , which adopts cubic  $F\bar{4}3m$  symmetry at ambient conditions.<sup>49</sup> For A = Na, the tilt pattern is



Fig. 3 Tilt patterns in Prussian blue analogues. The distribution of tilt patterns across PBAs with various A-site cations, where 'A' denotes the absence of A-site cations. The space group refers to the symmetry that the tilt gives rise to in the absence of further distortions. Tilts that (so far) are only known under pressure are indicated.

also stipulated by the hydration state, which will be discussed in the subsequent section. It follows that  $a^-a^-b^+$  is the tilt system present for the widest range of A-site cations and can be observed both at ambient and non-ambient conditions.

Finally, PBAs with large cations (Rb/Cs) may exhibit the uniaxial  $a^0a^0b^+$  distortion.  $\text{CsMnCo}(\text{CN})_6$  develops  $a^0a^0b^+$  tilts upon compression to 2 GPa, leading to  $P\bar{4}n2$  symmetry, and this constitutes the only known tilted Cs-based PBA to date.<sup>49</sup> The relatively high transition pressure highlights how large A-site cations reduce the tendency for tilting. Pressure- and photo-induced  $a^0a^0b^+$  tilts are known in Rb-based PBAs,<sup>49,50</sup> but also feature at ambient conditions in the Jahn–Teller distorted  $\text{RbCuM}'(\text{CN})_6$  ( $M = \text{Co}^{\text{III}}$  or  $\text{Fe}^{\text{III}}$ ).<sup>26,27</sup> Interestingly, the  $a^0a^0b^+$  distortion is exceedingly rare in double oxide perovskites,<sup>46</sup> albeit common in perovskite halides.<sup>51</sup> This illustrates how trends observed in inorganic perovskites cannot always be directly applied to their molecular counterparts.

### 3.3 M/M'-site composition

The transition metal ions may impact the propensity for structural distortions in PBAs by modulating the bond strength and thereby the flexibility. For example, the M–N bond strength



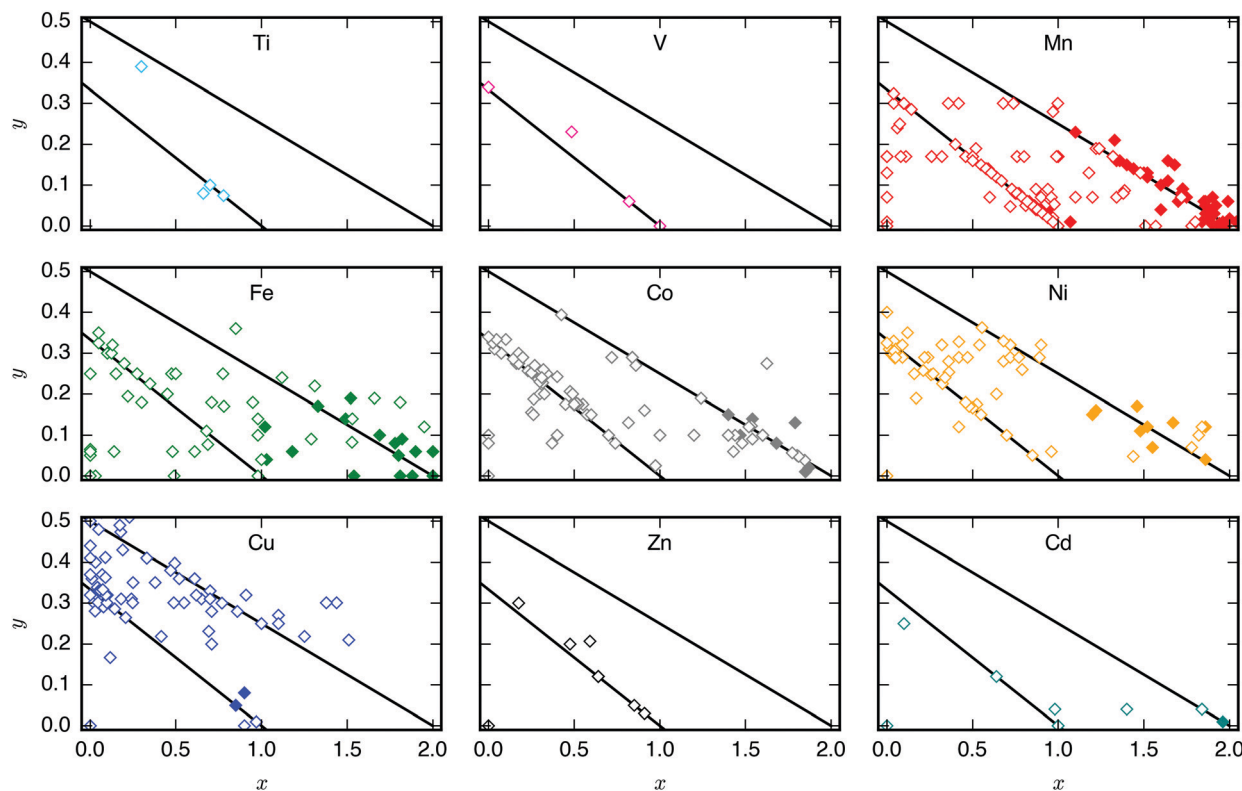


Fig. 4 The effect of M-site transition metal ions on the propensity for tilting. PBAs with composition  $A_xM[M'(CN)_6]_{1-y}\square_y$  ( $\square$  = vacancy) for various A, where filled (empty) symbols denote tilted (untilted) structures and the different panels refer to different M-site cations. The diagonal lines indicate compositions with a constant sum of the transition metal charges (+5 and +4).

in  $M\text{Pt}(\text{CN})_6$  depends on the identity of M according to the Irving–Williams series, with  $\text{NiPt}(\text{CN})_6$  ( $\text{CdPt}(\text{CN})_6$ ) as the most (least) rigid system.<sup>21</sup> In general, smaller M-site cations are believed to decrease the flexibility, which also manifests in more positive thermal expansion.<sup>52</sup> This agrees with the description of  $\text{Na}_x\text{NiFe}(\text{CN})_6$  as a zero-strain material with a low tendency for distortions upon Na intercalation.<sup>53</sup> To investigate this further, the data presented in Fig. 2 were replotted to highlight the effect of the different M-sites [Fig. 4].<sup>‡</sup> While more tilted systems are reported for M = Mn, Fe, Co, and Ni, this probably results from observational bias and small sample sizes for some of the other M-site metals. There is not enough data to draw any conclusion regarding the the role of the M-sites on tilting. However, as several tilted PBAs with M = Ni are reported,<sup>14,15</sup> the idea of Ni-PBAs as zero-strain materials may require reevaluation.

Jahn–Teller active M-site cations can contribute to tilting in certain Rb-containing PBAs.  $\text{Rb}_{0.85}\text{Cu}[\text{Fe}(\text{CN})_6]_{0.95}$  and  $\text{Rb}_{0.90}\text{Cu}[\text{Co}(\text{CN})_6]_{0.92}$  exhibit tilts,<sup>26,27</sup> whereas related structures with M =  $\text{Zn}^{\text{II}}$  or  $\text{Mn}^{\text{II}}$  are undistorted at ambient conditions.<sup>54,55</sup> Group-theoretical analysis indicates that the observed  $a^0a^0b^+$  tilt mode arises from a combination of the Jahn–Teller distortion and the occupational (M-point) Rb arrangement.<sup>26</sup>  $\text{Rb}_{0.58}\text{Mn}[\text{Fe}(\text{CN})_6]_{0.86}$  shows a Jahn–Teller distortion, but remains untilted due to its different (R-point)

Rb order.<sup>56</sup> As cubic symmetry is reported for  $\text{KCuFe}(\text{CN})_6$  and  $\text{CsCuFe}(\text{CN})_6$ ,<sup>27,57</sup> this phenomenon appears specific to Rb-containing systems. The interplay between tilts, Rb order and Jahn–Teller distortions is interesting and suggests that tilt engineering may be facilitated by introducing  $\text{Cu}^{\text{II}}$  ions in suitable systems.

There is less choice of metal ions for the M'-site, as they have to support octahedral low-spin coordination. Typical M'-site metals are  $\text{Cr}^{\text{III}}$ ,  $\text{Mn}^{\text{II/III}}$ ,  $\text{Fe}^{\text{II/III}}$ ,  $\text{Co}^{\text{III}}$ , and  $\text{Pt}^{\text{IV}}$ , with the largest prevalence of Fe due to its stability, low toxicity, and low cost. As a result, it is difficult to evaluate the influence of the M'-site on the tilting propensity, but this effect is likely to be minor. As the M'–C interaction is largely covalent and features strong  $\pi$ -backbonding from the metal to the cyanide, linear M'–C–N bonding is favoured. Indeed, the N typically shows larger mobility than the C atom, highlighting how most flexibility stems from the N–M linkage, rather than from C–M'.<sup>21</sup> A neutron diffraction study of the rhombohedrally tilted  $\text{Na}_{1.89}\text{Mn}[\text{Fe}(\text{CN})_6]_{0.97}$  also indicates a larger deviation from linearity at the N end of the cyanide relative to the C end.<sup>41</sup> Hence, the tilt propensity is presumably relatively unchanged as a function of M'-site substitutions, although experimental evidence is needed for confirmation.

### 3.4 Hydration

PBAs are nearly always synthesised from aqueous solution and the final products—if porous—thus contain water. It is

<sup>‡</sup> Compounds with formula  $\text{Cu}[\text{Fe}(\text{CN})_6]_{<0.67}$  feature Cu on both the A- and M-site,<sup>25</sup> meaning that Fig. 4 is less appropriate for M = Cu.



generally accepted that defective PBAs contain two types of water: coordinated water completing the coordination sphere of the M-site cation, and interstitial water, which may hydrogen bond to the coordinated molecules.<sup>58</sup> Due to the porous nature of these compounds, over 10 water molecules per cell are possible.<sup>58,59</sup> A-site deficient PBAs of formula  $MM'(CN)_6$  may also support *ca.* 4 water molecules per unit cell,<sup>60</sup> although these guest species are only weakly interacting with the framework. Regarding A-site-containing PBAs, systems with  $A = Li/Na$  are sufficiently porous to allow for interstitial  $H_2O$ , whereas increased A-site occupancy of larger alkali metals reduces the likelihood for solvent incorporation.<sup>61</sup> Although interstitial in nature, water can have a profound effect on *e.g.* the electrochemical and mechanical properties of the system.<sup>49,62</sup>

Unlike many other coordination polymers,<sup>63</sup> PBAs are not prone to major structural changes upon dehydration and typically remain cubic as the solvent is removed.<sup>21,59,64</sup> Nonetheless, a tilt transition was noted for  $Na_{1.32}Mn[Fe(CN)_6]_{0.83} \cdot 2.2H_2O$  upon further hydration.<sup>65</sup> To the best of our knowledge, this behaviour is a unique example of a solvent-induced phase transition in a Prussian blue analogue and further investigations will be valuable. While the role of water in PBAs is intriguing, it is associated with several challenges. Thermogravimetric analysis (TGA) shows a considerable dependence on the experimental setup,<sup>16,66</sup> and crystallographers are faced with the challenge of disordered solvent and the low scattering power of light elements. Studies into the role of water using local probes, perhaps using neutron radiation, would be beneficial.

While (de)hydration normally does not drive phase transitions, interstitial water sometimes dictates the tilt pattern. The distortion in  $Na_2MM'(CN)_6$  switches from monoclinic  $a^-a^-b^+$  to rhombohedral  $a^-a^-a^-$  upon solvent removal accompanied by increased amplitude of the distortion.<sup>11,41</sup> Whether K-based PBAs also show hydration-switchable tilts is unknown: monoclinic symmetry is reported for several compounds with high concentration of K and low hydration states,<sup>3,67</sup> and the larger radius of K leaves less free space for water molecules. Furthermore, water alters the pressure-induced phase transition of  $MnPt(CN)_6$ , which—at least in the hydrated case—is driven by tilts.<sup>49</sup> Therefore, while (de)hydration *per se* does not drive tilting, it has an impact on the tilts pattern induced by a different stimulus (pressure or sodiation). Yet, many questions remain to be answered, regarding *e.g.* the mechanism and critical water content required for switching.

### 3.5 Nonambient conditions

Changes in temperature can induce a wealth of phase transitions in oxide perovskites,<sup>46</sup> and thermal tilts also occur in some PBAs with high A-site concentrations.<sup>43,50,68</sup> For instance, tilts appear in  $Rb_{0.97}Mn[Fe(CN)_6]_{0.99}$  upon cooling to 91 K,<sup>50</sup> whereas a similar system with a lower Rb content,  $Rb_{0.58}Mn[Fe(CN)_6]_{0.86}$ , remains untilted to 30 K.<sup>56</sup> Phase diagrams as a function of temperature and A-site cation concentration have been created for certain PBAs, which highlight the possibility of thermal transitions between different tilt systems.<sup>69</sup> Further such efforts would be useful to understand

the relationship between the A-site cation content and the structural instabilities. Conversely, A-site deficient PBAs typically remain cubic down to low temperatures<sup>60,70,71</sup> as the soft tilt modes do not condense. This is interesting in its own right, as transverse low-energy phonons—such as tilts—typically underlie negative thermal expansion.<sup>72–74</sup>

Many PBAs undergo phase transitions when subjected to external hydrostatic pressure. For example,  $MnPt(CN)_6 \cdot nH_2O$  and  $Mn[Co(CN)_6]_{2/3} \cdot nH_2O$  show  $a^-a^-a^-$  tilts when compressed to  $\sim 1.5$  GPa, which provides rare examples of tilted PBAs without A-site cations.<sup>37</sup> The latter system demonstrates that vacancies do not necessarily disrupt the correlations between individual metal octahedra. However, this transition relies on the presence of interstitial water, as the dehydrated analogue retains its  $Fm\bar{3}m$  symmetry when compressed.<sup>49</sup> This is presumably a result of a hydrogen-bonded network of water molecules within the structure, which mediates correlations between individual metal sites separated by a vacancy. Likewise,  $FeCo(CN)_6$  amorphises at 10 GPa without prior phase transitions,<sup>75</sup> and  $FePt(CN)_6$  remains cubic to at least 3 GPa,<sup>76</sup> which shows that pressure does not universally induce tilts in A-site-deficient PBAs. Yet, as even Cs-based PBAs can be forced to tilt by the application of pressure,<sup>49,77</sup> compression is a useful method to obtain interesting phases and explore the tilting behaviour.

### 3.6 Tilt engineering

Tilt engineering—manipulating the octahedral tilting in order to achieve a desired property—is an appealing concept originally coined for oxide perovskites.<sup>10</sup> Like for the inorganic counterparts, tilts in Prussian blue analogues have clear functional implications and there is potential to improve the performance of PBAs by judicious manipulation of the tilts. Some examples are provided below and more can be anticipated.

Ferroelectricity is a technologically relevant property, yet is only allowed in compounds with polar space groups, which is a subset of the non-centrosymmetric space groups. As tilts inevitably lower the symmetry of the parent structure, they can be exploited to construct polar symmetries *via* improper ferroelectricity.<sup>78</sup> Here, nonpolar structural distortions are combined to generate a polar space group and allow for polar secondary order parameters, *e.g.* a displacement of the A-site cation. Tilts alone cannot lift all the inversion centres of the  $Fm\bar{3}m$  parent—as required for polar symmetry and ferroelectric properties; but this can be achieved by combining out-of-phase tilts ( $a^-$ ) with *R*-point occupational A-site cation order.<sup>79</sup> Such A-site arrangements are frequently found in  $AMM'(CN)_6$ , where  $A = Rb$  or  $Cs$ . For example,  $a^-a^-a^-$  tilts in A-site-cation-ordered PBAs yield the polar space group  $R3$ , whereas  $a^-a^-b^+$  drives  $Pn$  symmetry. The former symmetry may not be experimentally realisable as  $a^-a^-a^-$  tilts have not been observed for PBAs with ordered A-site cations, but the latter space group occurs in  $Rb_{0.87}Mn[Co(CN)_6]_{0.91}$  under modest pressure.<sup>49</sup> As noted above, the tilting behaviour appears largely independent of the transition metals and transition metal combinations known to give ferromagnetic behaviour, *e.g.* Ni–Cr,<sup>80</sup> could be







Fig. 5 Tilted structures of Rb-based PBAs. (a)  $\text{Rb}_{0.90}\text{Cu}[\text{Co}(\text{CN})_6]_{0.92}$ , where the tilting is driven by Jahn–Teller distorted Cu (blue) and the unusual Rb arrangement;<sup>26</sup> (b)  $\text{Rb}_{0.97}\text{Mn}[\text{Fe}(\text{CN})_6]_{0.99}$  under pressure;<sup>50</sup> (c)  $\text{Rb}_2\text{MnMn}(\text{CN})_6$  at ambient conditions;<sup>47</sup> and (d)  $\text{Rb}_{0.87}\text{Mn}[\text{Co}(\text{CN})_6]_{0.91}$  under pressure.<sup>49</sup>

## Author contributions

HLBB designed the study and collated the data. Both authors evaluated the data and contributed to the writing of the manuscript.

## Conflicts of interest

WRB is a co-founder of the company ALTRIS AB which produces Prussian white powder for sodium ion battery applications.

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