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## An extended Tolerance Factor approach for organic–inorganic perovskites†

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Goldschmidt's concept of ionic Tolerance Factors was recently shown to be a valuable guideline for the preparation of new compounds within the field of organic–inorganic perovskites. Here, we extend this approach and calculate Tolerance Factors for over 2500 amine–metal–anion permutations of the periodic table. The results suggest the potential existence of more than 600 undiscovered hybrid perovskites including alkaline earth metal and lanthanide based materials.

The large family of solid state perovskites with general formula  $ABX_3$  covers a wide range of fascinating properties, which include both application-oriented phenomena and fundamental physics and chemistry.<sup>1</sup> One of the key aspects that make perovskites so successful is the adaptability of this structure type towards A, B or X site substitution, which allows for tailoring of properties to meet particular requirements.<sup>2</sup>

During recent years a structurally related family, today known as organic–inorganic hybrid perovskites, has attracted a great deal of attention.<sup>3,4</sup> In this relatively young family the perovskite architecture is essentially maintained, while at least one ion – usually A or X – is substituted by an organic ion which makes the perovskite a *hybrid*. Today, research in this emerging field is largely driven by the intriguing properties of the hybrid perovskite  $[\text{CH}_3\text{NH}_3]\text{PbI}_3$  in thin film solar cell devices.<sup>5,6</sup> However, other hybrid perovskites, *e.g.* the family of perovskite-like metal formates  $\text{AB}(\text{HCOO})_3$  (A = protonated amine, B = divalent metal),<sup>7,8</sup> also show interesting properties such as multiferroic<sup>9</sup> behaviour and tuneable mechanical properties.<sup>10,11</sup>

Recently, Goldschmidt's Tolerance Factor (TF) concept, which has been a central mantra in the development of solid state perovskites for decades, was extended to the emerging field of organic–inorganic perovskites.<sup>12</sup> Similar to Goldschmidt's initial approach,<sup>13</sup> TFs of hybrid perovskites can be obtained by treating all ions as hard spheres or cylinders in the case of certain molecular anions. The definition of an ionic radius of organic ions is challenging,<sup>14</sup> but under the assumption of rotational freedom around the centre of mass and using given crystallographic data, a semi-empirical approach leads to

a consistent set of effective ionic radii for organic ions.<sup>12</sup> The concept of describing protonated amines in a perovskite structure as hard spheres is supported by microwave,<sup>14</sup> NMR and diffraction studies, as well as theoretical work. This reveals the highly dynamical nature of protonated amines within the perovskite cavity.<sup>15–18</sup> Following this concept, TFs of lead halide, divalent metal formate, and tetrahydroborate based perovskites have been calculated and very good agreement between experimental observations and theory was found.<sup>12,19,20</sup> For example, the TF concept has been successfully used as a guide in the synthesis of complex hydride perovskite-type materials, including the system  $[\text{CH}_3\text{NH}_3]\text{Ca}(\text{BH}_4)_3$ .<sup>19</sup> According to the current state of knowledge, hybrid perovskites are expected to form for TFs between 0.8 and 1, as in the case of solid state perovskites. This finding also includes hybrid formates with an anti–anti formate connectivity; however, for syn–anti bridged formates, the size of the  $\text{ReO}_3$ -like cavity is reduced and even TFs below 0.8 lead to a perovskite-like architecture.<sup>21</sup>

The TF concept can also help to explain the existence of low-dimensional materials with perovskite-like building motifs. The sole usage of amines that do not fit into the  $\text{ReO}_3$  cavity (TFs > 1) leads to low dimensional compounds, *e.g.*  $[\text{NC}_4\text{H}_8]\text{CdCl}_3$ ,  $[\text{C}_7\text{H}_7]\text{PbI}_3$  and  $[(\text{CH}_3\text{CH}_2)\text{NH}_3]\text{PbI}_3$ .<sup>22–24</sup> In such compounds 1D chains of face-sharing octahedra are separated by protonated amines. A change in stoichiometry consequently leads to a different class of 2D materials such as  $[\text{C}_2\text{H}_5\text{NH}_3]_2\text{CuCl}_4$ ,  $[\text{CH}_3\text{NH}_3]_2\text{FeCl}_4$  and  $[\text{C}_4\text{H}_9\text{NH}_3]_2\text{MnCl}_4$ ,<sup>25</sup> where single layers of corner sharing  $\text{MX}_6$ -octahedra are separated by large protonated amines. The partial substitution of the large amine with a smaller amine then leads to compounds such as  $((\text{C}_4\text{H}_9)\text{NH}_3)_2(\text{CH}_3\text{NH}_3)_2\text{Sn}_3\text{I}_7$  and  $(\text{NH}_2\text{CNH}_2)_2(\text{CH}_3\text{NH}_3)_2\text{Sn}_2\text{I}_8$ .<sup>26</sup> In these Ruddlesden–Popper type phases, perovskite-layers with TFs between 0.8 and 1.0 containing the smaller amine are separated by larger protonated amines that do not fit into the  $\text{ReO}_3$ -like cavity.<sup>4</sup>

Motivated by the latest developments in this fast moving field, we have calculated Tolerance Factors for a wide range of possible amine–metal–anion permutations in the periodic table

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† Electronic supplementary information (ESI) available: SI-Table 1, shows all 2352 calculated Tolerance Factors. SI-Fig. 1–6, show plots similar to Fig. 1 for fluoride, chloride, bromide, cyanide, borohydride and azide based permutations. See DOI: 10.1039/c5sc00961h







Fig. 2 Plotted are the effective radii of protonated amines  $r_{A,eff.}$  vs. ionic radii of the divalent metals  $r_B$  of hypothetical compositions. The figure shows (a) iodide based and (b) formate based permutations with TFs between 0.8 and 1.0. The plots highlight the influence of the linking anion on the size-ranges of protonated amines and divalent metals where a hybrid perovskite structure is expected to form. The anisotropy of the anti-anti bridged formate and the associated smaller effective radius ( $r_{X,eff.}$ ) leads to a larger  $ReO_3$ -like cavity, so that larger protonated amines can fit within the cavity for a fixed divalent metal. In the case of formates with a  $4^{12} \cdot 6^3$  topology and syn-anti connectivity, the size of the  $ReO_3$  cavity is reduced and even smaller protonated amines lead to a perovskite-like architecture, as recently shown for  $[NH_4]Cd(HCOOH)_3$ .<sup>21</sup>

and new synthetic procedures must be developed. For molecular anion based hybrids, solution chemistry approaches provide a powerful method in many cases.<sup>34,35</sup>

The wide applicability of TFs for hybrid perovskites suggests that the packing density is a crucial factor for the formation of a 3D hybrid perovskite framework. Within hybrid frameworks, the complexity of the bonding allows for tuning different properties over a wide range, e.g. band-gap engineering due to B or X site substitution in halide based compounds or altering magnetic properties in azido-bridged frameworks.<sup>34,36</sup> Hydrogen bonding interactions between the protonated amine and the cavity have been shown to have a large impact on the materials' properties.<sup>10</sup> For instance, in iodide and formate based frameworks, bonding interactions between amines and the frameworks influence the mechanical properties and are responsible for temperature-driven order-disorder transitions.<sup>15–17,32,37</sup>

In conclusion we calculated Tolerance Factors for over 2300 hypothetical amine-metal-anion permutations based on halides and molecular (organic) anions such as  $(HCOO)^-$ ,  $(CN)^-$  and  $(N_3)^-$ . Of these, 742 show TFs between 0.8 and 1 are predicted to adopt the perovskite structure. To our knowledge, the group of 742 compounds includes about 140 known examples

and more than 600 unknown hypothetical compounds. Interestingly, the doping of  $[CH_3NH_3]PbI_3$  on the lead site with  $Ca^{2+}$ ,  $Sr^{2+}$  and  $Cd^{2+}$  was recently reported and is encouraging for further research.<sup>38</sup> However, most of the predicted compounds herein, e.g.  $[CH_3NH_3]SrI_3$  and  $[CH_3NH_3]CaI_3$ , are not expected to be good electrical conductors. More likely, related to their hybrid nature, they may show ferroelectric and ferroelastic properties which are of great importance for switching devices and sensor applications. In this context, alkaline earth and first row transition metal based hybrids are of particular interest due to their high abundance.<sup>39</sup> Other compounds, such as lanthanide based hybrids, are expected to show interesting optical properties. Together with the large tuning adaptability of the perovskite structure, we expect that the family of hybrid perovskites will have a prominent influence on materials science in the future.

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