

# Optical activity from racemates

**To the Editor** — The relationship between chirality and optical activity is an important consideration for various fields of chemical, physical and biological research. For example, the determination of optical activity is a routine test of enantiomeric purity in organic synthesis. Chiral materials (or other non-centrosymmetric (NCS) materials) are also commonly used in optics and photonics to control the polarization of light. In the solid state, optical activity is intrinsic to the crystal structure. Although it is well established that optically active materials can form from any unit that is appropriately arranged — irrespective of the molecular chemistry of that unit — here we highlight that racemic pairs also fit into this category and can therefore be used to make optically active solids. This presents an important qualification to the widely held assumption that racemates are optically inactive.

One rule of crystal packing is that enantiomerically pure units must pack into chiral crystal structures<sup>1</sup>. Chiral materials may also be synthesized from only achiral building blocks<sup>2,3</sup>. In the synthesis of materials from achiral units, chirality is usually targeted by using chiral templates or solvents. On the other hand, right- and left-handed enantiomers must be related by symmetry to be strictly considered as a racemic compound<sup>4–7</sup> (to be consistent with the IUPAC definition of an enantiomer — one of a pair of molecular entities which are mirror images of each other and non-superposable — we do not consider kryptoracemic compounds as racemic because the enantiomers of opposite handedness are not strictly related by symmetry). Because only improper symmetry operations (that is, inversion centre, mirror plane and/or rotoinversion) can relate one enantiomer to its opposite, racemic compounds can only be classified into the 21 non-enantiomorphous point groups. In other words, whereas enantiomerically pure units must pack into chiral crystal structures, racemates, in the strictest sense of the word, must pack into non-chiral ones. Moreover, not only can the enantiomers of opposite handedness be arranged in these crystal classes<sup>8</sup>, but their arrangement can also induce such symmetries. Thus, enantiomers of opposite handedness can pack such that they are not related by an inversion centre, but instead by only improper

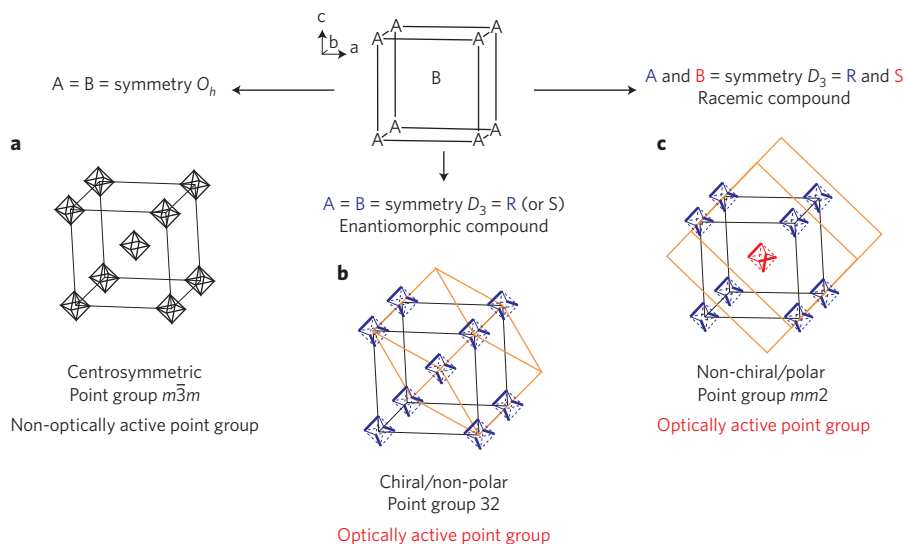
rotations or mirror planes leading to non-centrosymmetric point groups such as  $\bar{4}2m$  ( $D_{2d}$ ),  $\bar{4}$  ( $S_4$ ),  $mm2$  ( $C_{2v}$ ) or  $m$  ( $C_s$ ). This is illustrated in Fig. 1 in which the packing of centrosymmetric units (symmetry  $O_h$ ) leads to a centrosymmetric arrangement with symmetry  $m\bar{3}m$  (space group  $Im\bar{3}m$ ). If these units are pure enantiomers (symmetry  $D_3$ ), the arrangement leads to a chiral, non-polar material. If these units are non-polar racemates (symmetry  $D_3$ ), the same packing induces a polar arrangement with symmetry  $mm2$  (space group  $Aba2$ ) because only glide planes can relate the right- and left-handed enantiomers. Thus, the alignment of polar units is not the only available method to engineer polar materials. The racemic non-polar units can also be used as building units for this design.

The symmetry of the media is known to have an influence on its physical properties, and as stated by F. E. Neumann<sup>9</sup>, every symmetry element of the point group of a crystal structure must be included in the tensor symmetry of any of its physical properties. It is therefore possible to predict from the tensor symmetries which crystal structure can exhibit specific properties. A general consequence of this is that no

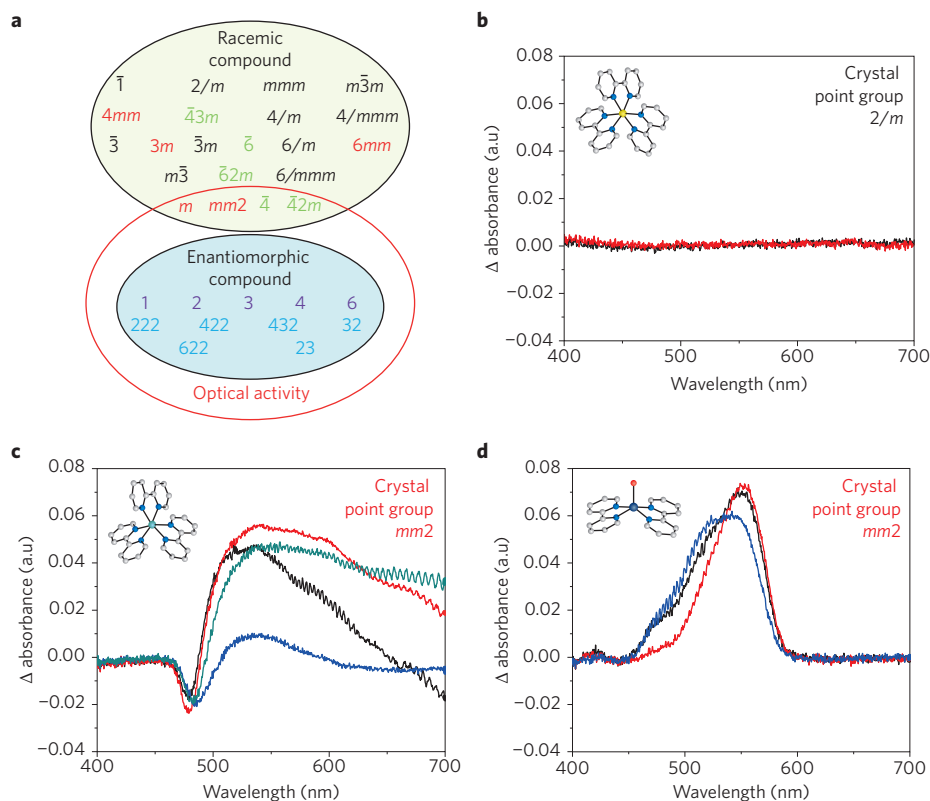
property described by polar tensors of odd rank and axial tensors of even rank can be observed in media with an inversion centre. For example, pyroelectricity (first rank polar tensor), optical activity (second rank axial tensor) and piezoelectricity/linear electro-optic effect (third rank polar tensor) can only be observed in non-centrosymmetric media. In particular, optical activity which can be described by a second rank axial tensor will be specific to the eleven enantiomorphous point groups (1, 2, 3, 4, 6, 222, 422, 432, 32, 622 and 23) and four non-enantiomorphous point groups ( $\bar{4}2m$ ,  $\bar{4}$ ,  $mm2$  or  $m$ ; Fig. 2a) (refs 10–12). Indeed, optical rotation from non-enantiomorphous compounds has been demonstrated previously<sup>13–18</sup>.

As shown in Fig. 2a, optical activity can be observed in 15 crystallographic point groups. On the other hand, enantiomers of opposite handedness can arrange into 21 crystallographic point groups. Thus, the optical activity and racemic compound groups are not independent: the crystal classes  $\bar{4}2m$ ,  $\bar{4}$ ,  $mm2$  or  $m$  belong to both groups and, consequently, racemic compounds can be optically active.

To confirm optical activity in racemic materials, we synthesized



**Figure 1** | Representation of the arrangements of A and B units in CsCl-type packing. **a–c**, If A and B are octahedral, the resulting structure **(a)** (space group  $Im\bar{3}m$ ) cannot be optically active. If A and B are enantiomers (symmetry  $D_3$ ) with the same handedness (either R or S), the resulting structure **(b)** (space group  $R32$ ) is chiral, non-polar and can be optically active. If A and B are enantiomers (symmetry  $D_3$ ) with opposite handedness (racemic compounds, R and S), the resulting structure **(c)** (space group  $Aba2$ ) is non-chiral, polar and can be optically active. The new unit cells resulting from the search of symmetry elements are represented in orange.



**Figure 2 |** Racemic compounds and optical activity. **a**, The 32 crystallographic point groups and optical activity. Centrosymmetric, black; polar and non-chiral, red; chiral and non-polar, blue; chiral and polar, purple; non-centrosymmetric, non-chiral and non-polar, green. **b–d**, Circular dichroism spectra of  $[\text{Ni}(\text{bpy})_3](\text{MoO}_2\text{F}_4)\cdot 5\text{H}_2\text{O}$  (space group  $C2/c$ , point group  $2/m$ ) (**b**);  $[\text{Zn}(\text{bpy})_3](\text{CrO}_4)_{0.5}\text{NO}_3\cdot 6.5\text{H}_2\text{O}$  (space group  $Ccc2$ , point group  $mm2$ ) (**c**); and  $[\text{Cu}(\text{H}_2\text{O})(\text{bpy})_2][\text{HfF}_6]\cdot 3\text{H}_2\text{O}$  (space group  $Pna2_1$ , point group  $mm2$ ) (**d**). Each line in the plots corresponds to different locations through the same face of the crystals and represents the difference in absorbance between right and left circularly polarized light due to optical rotation.

compounds containing chiral metal trischelates  $[\text{M}(2,2'\text{-bpy})_3]^{2+}$  (M, metal; bpy, bipyridine) with the symmetry  $D_3$  (Fig. 2b,c). We selected from the literature  $[\text{Ni}(\text{bpy})_3](\text{MoO}_2\text{F}_4)\cdot 5\text{H}_2\text{O}$  (**1**) which crystallizes in the centrosymmetric space group  $C2/c$  (point group  $2/m$ )<sup>19</sup>, and  $[\text{Zn}(\text{bpy})_3](\text{CrO}_4)_{0.5}\text{NO}_3\cdot 6.5\text{H}_2\text{O}$  (**2**) which crystallizes in the space group  $Ccc2$  (point group  $mm2$ )<sup>20</sup>. In addition, optical measurements were carried out on  $[\text{Cu}(\text{H}_2\text{O})(\text{bpy})_2][\text{HfF}_6]\cdot 3\text{H}_2\text{O}$  (**3**), crystallizing in the space group  $Pna2_1$  (point group  $mm2$ ), in which we have previously shown that the arrangement of racemic units  $[\text{Cu}(\text{H}_2\text{O})(\text{bpy})_2]^{2+}$  (symmetry  $C_{2v}$ ) were responsible for its polarity<sup>8</sup> (Fig. 2d). Figure 2b represents the single-crystal circular dichroism measurement of **1**, showing the expected absence of optical activity in the visible light region. This is in contrast to Fig. 2c,d which show distinct peaks in the respective circular dichroism spectra for compounds **2** and **3**, despite being racemic materials.

As optical activity is related to the symmetry of the media, one can identify optically active materials from their crystal structures and also deduce the symmetry from optical measurements. In the case of enantiomorphous media (liquid or solid), the average tensorial components of the optical activity is not equal to zero<sup>21</sup>. This means that the random crystallite orientation can lead to optical activity. However, in the specific case of non-enantiomorphous compounds crystallizing in the point groups  $\bar{4}2m$ ,  $\bar{4}$ ,  $mm2$  or  $m$  such as the optically active racemates, the second rank, axial tensor describing optical activity corresponds to the symmetry  $\bar{4}m$ . Thus, the optical activity is equal and opposite in two perpendicular axes of the single crystal leading to the cancellation of the activity for powders.

The arrangement of racemic units is key to breaking the centrosymmetry of these crystal structures and leads to the symmetries  $\bar{4}2m$ ,  $\bar{4}$ ,  $mm2$  or  $m$ . Hence, the presence of optical activity in the materials **2** and **3** does not depend on the

intrinsic characteristics of the racemic units but on their arrangement. Different arrangements of similar racemic metal trischelates (symmetry  $D_3$ ) can crystallize into a centrosymmetric structure such as **1** and be optically inactive or into a non-centrosymmetric structure belonging to one of the four point groups  $\bar{4}2m$ ,  $\bar{4}$ ,  $mm2$  or  $m$ , such as **2**, and be optically active. We estimate that racemic compounds crystallizing in these four point groups represent approximately 5% of all crystalline racemates. A traditional approach to synthesize chiral, optically active materials is to use chiral building units, and so the optical activity from racemates could instruct further technological developments without the practical constraints of time-consuming and expensive enantiomeric purifications. In any event, these observations serve to correct a clear deficit in our understanding of the optical properties of racemates. □

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