Organometallic polymorphism and phase transitions†

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Received 21st March 2000
Published on the Web 8th June 2000

The possibility of obtaining the same organometallic substance in different crystal forms, which may or may not interconvert *via* a phase transition, is reviewed. The occurrence of reversible order-to-order and order-to-disorder phase transitions, usually associated with reorientational processes in the solid state for mono- and polynuclear organometallic complexes, is addressed. Pseudo-polymorphism arising from co-crystallisation of solvent molecules and the preparation and interconversion of pseudo-polymorphs by non-solution methods are discussed.

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1 Introduction

Polymorphism is the property of a substance to exist in different crystalline phases resulting from different arrangements of the molecules in the solid state.[1] Conformational polymorphism occurs when a molecule can adopt different shapes due to internal degrees of freedom, *e.g.* different low-energy conformations of an organic species, or different relative dispositions of ligands in a metal–organic species.[2] Pseudo-polymorphism refers to cases in which a given substance is known to crystallise with different amounts or types of solvent molecules.[3]

The intriguing possibility of isolating the same compound in different crystals continues to attract both scientific and utilitarian interest. Even though polymorphic modifications contain exactly the same substance, they differ in chemical and physical properties such as density, diffraction pattern, solid state spectroscopy, melting point, stability, reactivity, but also mechanical properties, *e.g.* those relevant for comminution and tableting.[4] Importantly, many drugs exist in polymorphic modifications which have different efficiency of assimilation because of the difference in solubilities.[5a] The enormous economic implications of this aspect are witnessed, *inter alia*, by the number of patent litigations involving drug companies.[5b] There is a vast literature on organic polymorphism; the interested reader may find recent entry points in refs. 1–6.[6]

There is consensus on the idea that—no matter whether one is considering polymorphism, pseudo-polymorphism or conformational polymorphism—the molecule must have the same (time average) structure in solution or in the melt. Dunitz has recently discussed in remarkably clear terms the relationship between the rate of interconversion between isomers and the existence of polymorphic modifications.[7] Separate crystallisation may be attained if the rate at which two isomers interchange in solution is slow with respect to the time required for nucleation. *Concomitant polymorphs* are those obtained from the same crystallisation process. This topic has been recently discussed by Bernstein *et al*.[8]

The aim of this article is essentially twofold: (i) to take polymorphism from the more traditional field of organic chemistry to the neighbouring area of organometallic chemistry, emphasising analogies and differences between the two fields; and (ii) to discuss some alternative ways to prepare and characterise new polymorphs or pseudo-polymorphs by non-solution methods. The hope is to stimulate research in this exciting field.

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† Dedicated to Professor Alberto Ripamonti on the occasion of his 70th birthday.

DOI: 10.1039/a909042h

It is educative to compare the percentage of polymorphic forms in each class of compounds available in the Cambridge Structural Database.[9] At the time of writing (March 2000), while organic polymorphs represent 4.1% of all organic compounds, the percentage increases slightly (5.5%) if the search is confined to compounds containing a bond between a transition metal atom and carbon (*i.e.* with the exclusion of coordination compounds), if coordination compounds are included, however, the percentage drops to 2.1%. Although these small figures support the idea that the vast majority of polymorphs in all chemical classes have been discovered by serendipity, it is noteworthy that there is a slightly higher chance of coming across an organometallic polymorph than in any other class of compounds.

Since structural flexibility is a distinctive characteristic of organometallic molecules (because of the often delocalised nature of the metal–ligand bonding and/or the availability of almost isoenergetic, though geometrically different, bonding modes for the same ligand) the intriguing relationship between molecular non-rigidity and crystalline phase transitional behaviour[10] needs to be taken into account when approaching organometallic polymorphism. Many organometallic molecules exist in different isomeric forms that interconvert *via* low-energy processes (*viz.* reorientation, diffusion, scrambling, and fluxionality) both in the gas phase and in the condensed state.[10]

It should be pointed out that studies of polymorphism fall of their own right into the mainstream of (molecular) crystal engineering.[11] Predicting,[12] on the basis of the knowledge of the molecular structure and of the inter-molecular interactions at work in the solid state, and making new polymorphic forms[13] of the same substance are indeed a means of preparing *crystals with a purpose*.[14] The ultimate goal is to attain (and possibly control) different solid state properties by changing the way molecules are organised in the solid state.

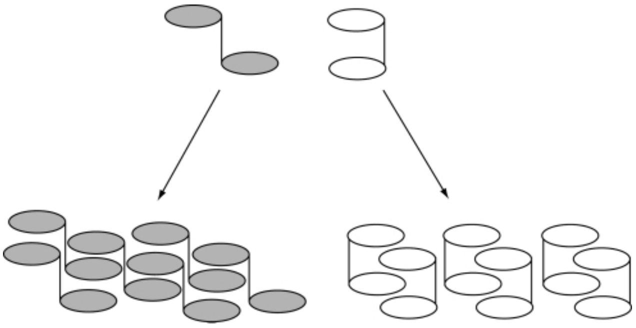
2 Organometallic polymorphism: a need for a broader perspective

Metal–ligand delocalised bonding, variable oxidation states (hence variable ionic charges) for the same metal and the availability of isoelectronic metal atoms are distinctive characteristics of organometallic systems that are not observed with purely organic systems. The implication is that “organic-type” classifications of polymorphism tend to be too restrictive for organometallic species. In the following we will try to expand this view.

2.1 Polymorphs formed by conformational isomers

Conformationally flexible organometallic molecules give rise to organometallic conformational polymorphism.[15] The molecular structure is affected along soft deformational paths by the change in crystal structures, and different conformations (usually different rotamers, see Scheme 1) as well as different structural isomers (*e.g.* terminal, bridging, semi-bridging ligands) of a fluxional process can be isolated. A textbook example of conformational polymorphism is provided by ferrocene, for which one room-temperature disordered and two low-temperature ordered crystalline forms are known.[7] At the crystal level they differ in the relative orientation of the cyclopentadienyl rings and in small rotations of the molecules, so that the phase transition mechanism requires only low-energy reorientation of the rings and a limited motion of the molecules in the crystal structure.[7,16]

Crystals of structural isomers related by low-energy interconversion pathways, such as transition metal cluster carbonyls with different distributions of bridging and terminal ligands, can also be assimilated to conformational polymorphs. Since the structural isomers correspond to different energetic minima along the interconversion pathway, less thermodynamically stable isomers may be isolated in the solid state if the enthalpy difference is compensated by a gain in packing energy. For instance, the two known forms of $Ru_6C(CO)_{17}$ contain a total of three isomers that differ in the rotameric conformation of the tricarbonyl units on the two apices and in the pattern of terminal, bridging, and semi-bridging CO’s around the molecular equator.[17] The existence of these rotamers indicates that the carbonyl units lie on a flat potential energy surface, so that the conformational choice is chiefly under intermolecular control. Similarly, the hydrido–borido cluster $HRu_6B(CO)_{17}$ is known in two crystalline forms in which the molecules differ in the location of the H(hydride) atom over the cluster surface and in the orientation of the tricarbonyl units.[17]



Scheme 1 A schematic representation of the relationship between molecular and crystal structures of conformational isomers.

2.2 Crystals of isoelectronic isomers

An intriguing possibility offered by organometallic complexes is that of changing the chemical composition without substantial changes in the distribution of ligands on the molecular periphery. This is easily achieved by substituting one or more metal atoms for other metals in the same subgroup of the Periodic Table (*e.g.* a kind of isomorphous substitution). Isoelectronic replacement of the metal core often leaves the topology of the outer structure unaffected. For example orthorhombic ruthenocene is isomorphous with orthorhombic ferrocene[7] but is obviously different from monoclinic ferrocene. Isoelectronic isomers may thus form the same crystal structure, being similar both at the molecular and the supramolecular level, or may adopt different crystal structures because of a different balance between intermolecular interactions and close packing. It is worth stressing, in this context, that differences in space groups are not necessarily diagnostic of differences in crystal structures. When correlations between molecular and crystal structures are sought, it is always necessary to ‘look inside’ the crystal. Indeed, the observation of the same space groups and of similar unit cell dimensions does not necessarily imply the same distribution of intermolecular interactions, *i.e.* the same supramolecular structure. Different space groups, on the other hand, may be associated with very similar general features of the packing.

Textbook examples of the intricate relationships between flexible molecular structure and crystal structure are provided by the three isoelectronic binary carbonyls $Fe_3(CO)_{12}$, $Ru_3(CO)_{12}$ and $Os_3(CO)_{12}$. $Fe_3(CO)_{12}$ possesses two bridging and ten terminal CO ligands (but see below for the phase transition behaviour) while the two heavier clusters possess twelve terminal CO’s, and are isomorphous in their crystals.[18] Analogously, the two arene clusters $[(\mu_3\text{-}\eta^2\text{:}\eta^2\text{:}\eta^2\text{-}C_6H_6)M_3(CO)_9]$ (M = Ru and Os) possess the same molecular structure but differ at the crystal level (see Fig. 1).[19]

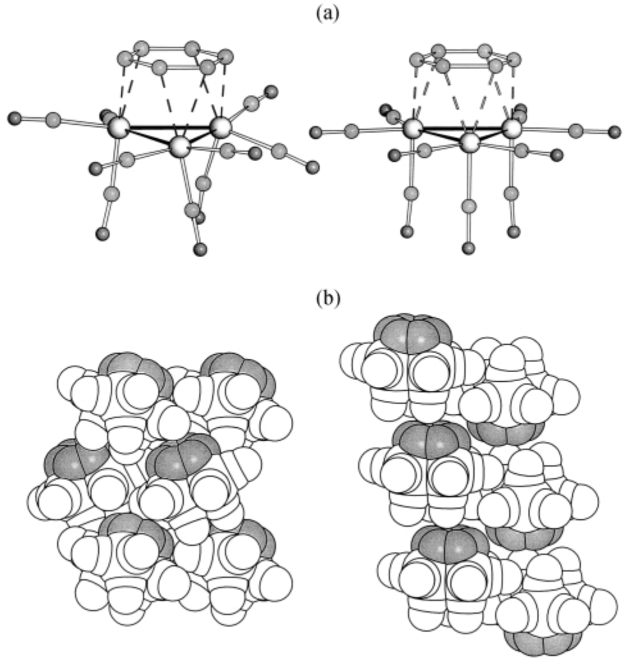


Fig. 1 Schematic representation of the relationship between (a) molecular and (b) crystal structure of $[(\mu_3\text{-}\eta^2:\eta^2:\eta^2\text{-}C_6H_6)M_3(CO)_9]$ (left hand side M = Ru, right hand side M = Os). H atoms are omitted for clarity.

There are several other examples of families of isoelectronic isomers such as $M_4(CO)_{12}$ (M = Co, Rh and Ir) and $[(C_5H_5)_3M_3(CO)_3]$ (M = Co, Rh and Ir).[20] Historically, all these complexes have been studied for their differences in bonding and molecular chemistry; they now provide a way to learn more about the relationship between molecular and crystal structure and about the role of specific pairwise interactions in solid-state cohesion, hence their effect on the particular *molecular* structure adopted in the solid state. For example, in $Fe_3(CO)_{12}$ the role of long range interactions between the M_3 cores of neighbouring clusters can be expected to be less important than in the case of $Os_3(CO)_{12}$, because the total number of electrons involved in the M_3 moiety is much higher for M = Os (228) than for M = Fe (82). On the other hand the C··C and C··O external interactions should be approximately the same, as both molecules are globular in shape and have roughly the same volume. The difficulty in accounting for the contribution of metal atoms is one of the major drawbacks in the calculation of packing energies, hence in the generation of theoretical crystal structures, of transition metal complexes.[21]

The two complexes *cis*-$[IrH(OH)(PMe_3)_4][PF_6]$ and *cis*-$[IrH(SH)(PMe_3)_4][PF_6]$ are mononuclear electronic isomers which differ in the orientation and pattern of intermolecular interactions established by the XH ligand (X = O, S), see Fig. 2.[22] The hydrogen atom bound to the metal co-ordinated oxygen in the first complex exhibits a close contact with the Ir-bound hydride ligand [H··H 2.334 Å]. In the isoelectronic SH-derivative the orientation of the SH-group is such that the sulfur-bound hydrogen atom points far away from the hydride ligand and towards the nearest PF_6^- anion, forming a charge assisted $S–H\cdots F^-$ interaction. DFT calculations have been used to demonstrate that the two different topologies result from a balance between intra- and inter-molecular energy terms, hence that the anions are not innocent spectators but competitors in the formation of interactions with the XH groups.

2.3 Polymorphism arising from static/dynamic disorder and from order–disorder phase transitions

Ordered and disordered crystals of the same molecules may have different point symmetry arising from static/dynamic disorder affording different crystal forms which may or may not interconvert *via* a phase transition.[23] The most common case is that of organometallic molecules which are globular in shape undergoing phase transitions with formation of plastic or semi-plastic phases, characterised by short range orientational disorder and long range order.

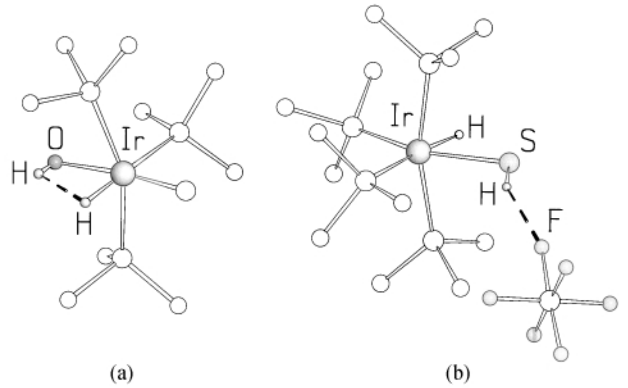


Fig. 2 Comparison between the intra-O–H··H and the inter-S–H··F interactions in crystalline *cis*-$[IrH(OH)(PMe_3)_4][PF_6]$ (a) and *cis*-$[IrH(SH)(PMe_3)_4][PF_6]$ (b). Hydrogen atoms of the methyl groups, and the PF_6^- anion in the –OH derivative have been omitted for clarity.

An example of non-interconverting polymorphs is provided by another textbook system, namely ferrocenedicarboxylic acid, $[(\eta^5\text{-}C_5H_4COOH)_2Fe]$.[24] The molecule is known in two forms that differ in the relative orientation of the hydrogen bonded molecular pairs (Fig. 3). Two polymorphic modifications are also known for the complex $[(\eta^2\text{-fumaric acid})\text{-}Fe(CO)_4]$ (forms I and II). In form I, the fumaric acid ligands

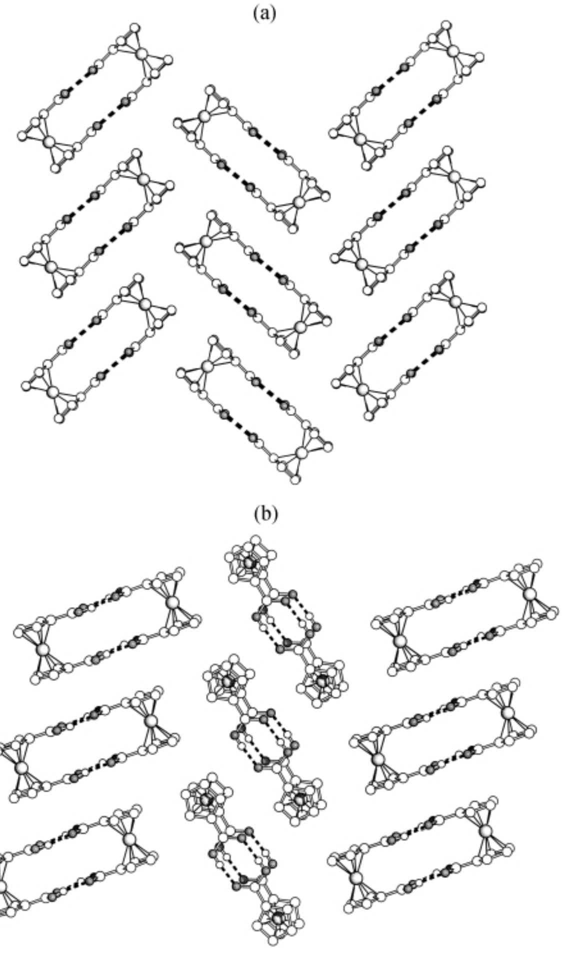
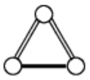
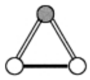
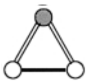
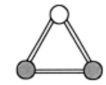
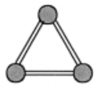
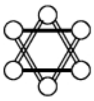
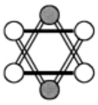
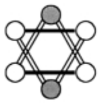


Fig. 3 Comparison between (a) disordered (monoclinic) and (b) ordered (triclinic) forms of $[(\eta^5\text{-}C_5H_4COOH)_2Fe]$. The disorder in the monoclinic form affects the –COOH–HOOC– hydrogen bonded ring system and is not shown.

Table 1 The disorder and phase transitions observed for the $M_3(CO)_{12}$ family (up to 1999!)

$[Fe_3(CO)_{12}]$ 10 CO_t, 2 CO_{br}	$[Fe_2Ru(CO)_{12}]$ 10 CO_t, 2 CO_{br}	$[Fe_2Os(CO)_{12}]$ 10 CO_t, 2 CO_{br}	$[FeRu_2(CO)_{12}]$ 12 CO_t	$[Ru_3(CO)_{12}]$, $[Os_3(CO)_{12}]$ 12 CO_t
				
$T < 210$ K[a] M_3 partial ordering ⥮ phase transition 210 K ⥮ M_3 "Star-of-David" disorder $T > 210$ K	M_3 ordered at 223 K (*Pn*) ⥮ 298 K partial M_3 disorder ⥮ phase transition *T ca.* 313 K ⥮	M_3 ordered at 120–220 K (*Pn*) ⥮ 298 K partial M_3 disorder (*Pn*) ⥮ phase transition $T \approx 373$ K ⥮ $T > 373$ K	M_3 order at $T = 173$ K (*C2cb*) ⥮ phase transition 228 K ⥮ M_3 disorder at 228–298 K (*Ccmb*)[b]	M_3 order no phase transition
				
	$T > 313$ K M_3 50:50 "Star-of-David" disorder ($P2_1/n$)	M_3 50:50 "Star-of-David" disorder ($P2_1/n$)[c]		

[a] In a supercell with 4.5 molecules in the asymmetric unit. [b] "Extended Star-of-David" disorder. [c] High temperature data were not collected in view of the isomorphous relationships and of the centrosymmetry of the space group; a 50:50 disorder as in $Fe_2Ru(CO)_{12}$ is assumed.

form ribbons of ligands joined by carboxylic rings. Interestingly, the same arrangement is observed in crystalline fumaric acid, which also possesses two polymorphic forms both based on molecular chains interlinked *via* hydrogen bonded carboxylic rings. In form II of $[(\eta^2\text{-fumaric acid})Fe(CO)_4]$ the carboxylic rings form a catemer-type pattern.[15]

Many examples of order–disorder organometallic crystal-to-crystal transformations are available, and their review is beyond the scope of this article. Literature entries on the behaviour of thiophene chromium tricarbonyl $[(\eta^5\text{-}C_4H_4S)(CO)_3Cr]$, on substituted ferrocene derivatives such as $[(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4CHO)Fe]$ and $[(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4CMeO)Fe]$, and on salts of the type $[(\eta^6\text{-}FC_6H_5)(\eta^5\text{-}C_5H_5)Fe][A]$ [A = AsF_6^-, PF_6^-, SbF_6^- and BF_4^-], which are all known to undergo order–disorder phase transitions, can be found in ref. 10.

The interpretation of the solid state and solution dynamic behaviour of the family of complexes $[M_3(CO)_{12}]$ (M = Fe, Ru, Os) has provoked heated debates through 30 years of cluster chemistry.[25] Recently, variable temperature X-ray diffraction experiments have demonstrated that the isoelectronic molecules $[Fe_3(CO)_{12}]$, $[Fe_2Ru(CO)_{12}]$, $[Fe_2Os(CO)_{12}]$ and $[FeRu_2(CO)_{12}]$ show disorder of a dynamic nature, associated with metal core reorientation, accompanied by reversible order–disorder phase transitions.[26] Some relevant information on the phase transitional behaviour of $[M_3(CO)_{12}]$ clusters is collected in Table 1. In the case of $[Fe_2Ru(CO)_{12}]$, for instance, the disordered room temperature structure becomes fully ordered at 220 K while, on increasing the temperature to 313 K, the crystal becomes isomorphous with crystalline $[Fe_3(CO)_{12}]$. These reversible changes are accompanied by an increase in the metal atom disorder, from the completely ordered structure at 223 K to a statistically disordered (1:1) "Star of David" structure at 323 K. Crystals of $[FeRu_2(CO)_{12}]$ show a similar behaviour, passing from an ordered structure at 173 K to an extended "Star of David" disordered structure above the phase transition temperature (228 K). The parent cluster $[Fe_3(CO)_{12}]$ undergoes a phase transition at ~210 K to another monoclinic phase with a partial ordering of the metal atom triangles. The asymmetric unit is comprised of four complete molecules and one half-molecule of $[Fe_3(CO)_{12}]$, and one of these molecules is completely ordered.[26] The relationship between local disorder and phase transitions is shown in Fig. 4. It is fascinating to think that all this knowledge on the behaviour with temperature has been put together in the past few years. The structural information of a dynamic nature has been 'hidden' for many years of the $[M_3(CO)_{12}]$ saga, and has only been made available thanks to the progress in X-ray diffraction devices.

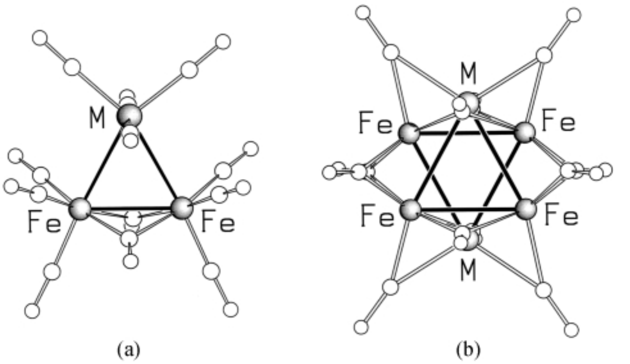


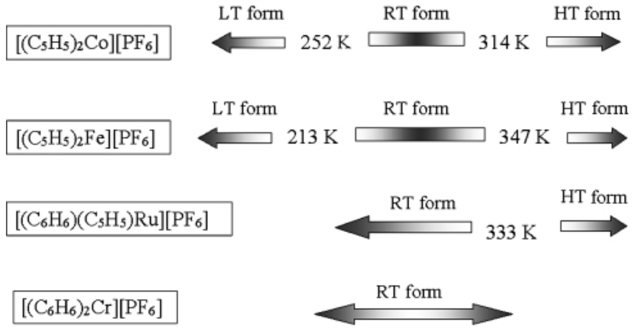
Fig. 4 The order (a)–disorder (b) relationship in clusters $[Fe_2M(CO)_{12}]$ (M = Fe, Ru, Os). The 50:50 "Star-of-David" disorder is present at room temperature in $[Fe_3(CO)_{12}]$ but is attained only at higher temperatures by the heavier mixed-metal clusters.

It should be stressed, however, that the presence of disorder does not *per se* indicate the existence of different patterns of intermolecular interactions (which is what identifies crystal isomers, *viz.* polymorphs). Since the appearance of disorder in crystals depends on the averaging process over time and space of the diffraction data, the same average image may result from superimposition of differently orientated crystallites with dimensions of a few nanometers (mosaic disorder), from microscopic or macroscopic twinning, or from overlap of a random distribution of unit cells containing molecules in different orientations (local disorder) or with orientation changing with time (dynamic disorder). Clearly, in the case of mosaic disorder the environment of each molecule is the same as in an ordered crystal.

2.4 Order-to-order phase transitions between enantiotropic systems

Within a broader, supramolecular perception of the nature of a crystal,[27] molecular crystal polymorphism can be seen as a form of crystal isomerism: just as the different distributions of chemical bonds for molecules of identical composition give rise to structural isomers (*e.g. cis*- and *trans*-isomers), different distributions of intermolecular interactions give rise to structural isomers of the same molecular aggregate. Hence, the change in crystal structure associated with an interconversion of polymorphs, *i.e.* a solid-to-solid phase transition (between ordered phases), in which intermolecular interactions are rearranged, can be regarded as the crystalline equivalent of an isomerisation at the molecular level. As pointed out by Dunitz,[7] however, phase transitions imply an extraordinary level of cooperativity, which is not relevant in solution. Moreover, when the phase transition takes place there is complete conversion of one crystal into the new one without formation of an equilibrium mixture of reactant and product.

We will now discuss the polymorphic relationship and phase transition behaviour of $[(\eta^5\text{-}C_5H_5)_2M][PF_6]$ (M = Co, Fe). The two crystalline materials are isomorphous at room temperature[28] and have been shown, by variable temperature X-ray diffraction experiments and differential scanning calorimetry, to undergo two reversible phase changes (M = Fe, *ca.* 213 and 347 K, M = Co, *ca.* 252 and 314 K), *i.e.* the range of thermal stability of the intermediate phase varies from *ca.* 62 K in the case of Co to *ca.* 134 K in the case of Fe (see Scheme 2). In both cases, the phase transitions could be followed on the single crystal X-ray diffractometer and diffraction data were collected on the same crystal specimen. The ordered room temperature monoclinic crystal transforms, on cooling, into another ordered monoclinic crystal with a different β-angle and relative orientations of the two independent cations. On heating, the crystals of the two species transform into semi-plastic systems containing ordered $[PF_6]^-$ anions and orientationally disordered $[(\eta^5\text{-}C_5H_5)_2M]^+$ cations.



Scheme 2 Schematic view of the relationship between different phases in solid $[(\eta^5\text{-}C_5H_5)_2M][PF_6]$ (M = Co, Fe), $[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru][PF_6]$ and $[(\eta^6\text{-}C_6H_6)_2Cr][PF_6]$.

The crystal structure of $[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru]^+$ shows analogies in packing arrangement with both the “dynamic” crystals $[(\eta^5\text{-}C_5H_5)_2M][PF_6]$ (M = Co, Fe) and with the “static” crystal of the bis-benzene chromium analogue, $[(\eta^6\text{-}C_6H_6)_2Cr][PF_6]$. In spite of the difference in molecular structure, the chromium salt crystallises in a manner that is strictly related to that of the low temperature phases of Co and Fe, and does not appear to undergo phase changes on cooling.[29] While topologically intermediate between the bis-cyclopentadienyl and the bis-benzene sandwich structures, crystalline $[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru]^+$ does not undergo a low-temperature phase transition on decreasing the temperature down to 223 K on the DSC instrument and down to 100 K on the diffractometer, showing only an order–disorder phase transition on increasing the temperature. On heating, the endothermic peak occurs at 332.5 K. The enthalpy difference associated with the transition is 4.16 kJ mol^{-1}, which is comparable with the values obtained from the DSC measurements for the order–disorder phase transitions in $[M(\eta^5\text{-}C_5H_5)_2][PF_6]$ (3.05 kJ mol^{-1} for M = Co, 4.50 kJ mol^{-1} for M = Fe).

In all of these structures there are two ‘types’ of cations: those lying in plane with the axes passing through the centres of the rings at *ca.* 90° and those ‘oblique’ over the plane. The $[PF_6]^-$ anions occupy the interstices and form a nearly cubic box in which the cations are encapsulated. Differences between the crystals arise from the relative orientation of the two types of cations as shown in Fig. 5. Data on these phase transition behaviours are summarised in Table 2 and are graphically represented in Scheme 2.

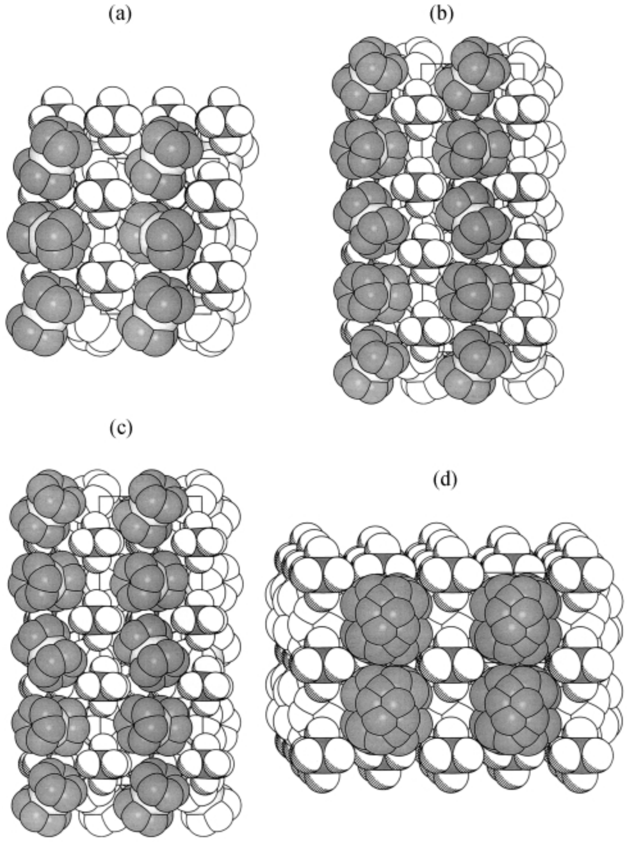


Fig. 5 Comparison between the cation (shaded units) arrangements in $[(\eta^5\text{-}C_5H_5)M][PF_6]$ at room temperature (M = Co, Fe) (a), $[(\eta^6\text{-}C_6H_6)_2Cr][PF_6]$ (b) and $[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru][PF_6]$ at room (c) and high temperature (d).

The most remarkable aspect of these structures is, however, the fact that the ordered distribution of cations and anions observed in the room temperature structure is fully restored on cooling the HT phases. The most sensible rationale for the phenomenon is the same for all these crystals: the high temperature *apparently cubic* phases are the result of an experimental average over time and space of domains that retain the original monoclinic structure but with disordered cobalticinium cations occupying the “boxes” defined by ordered anions. This model provides a rationale for the order–disorder reversibility, *i.e.* for the restoration of the non-degenerate ordered distribution on cooling crystalline $[(\eta^5\text{-}C_5H_5)_2M][PF_6]$ (M = Co, Fe), as well as $[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru][PF_6]$, which would not be understandable if the crystals had reached a plastic state.

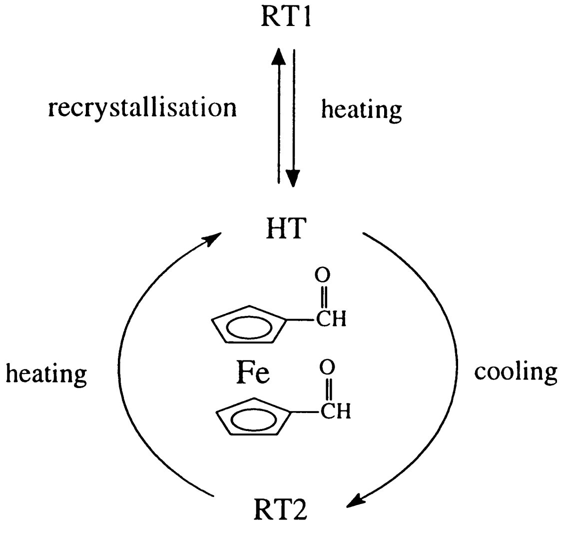
Another interesting order–disorder relationship was observed on studying crystalline bis-formylferrocene $[Fe(\eta^5\text{-}C_5H_4CHO)_2]$.[30] The room temperature phase (RT-1) undergoes, on heating, a first solid-to-solid phase transition (RT-1 → HT) at *ca.* 311 K. The ΔH associated with the transition [14.0 kJ mol^{-1}] from room to high temperature is slightly higher than the values reported in Table 2 for $[M(\eta^5\text{-}C_5H_5)_2][PF_6]$ (M = Co, Fe) while it is comparable with the value (12.1 kJ mol^{-1}) found for the mono-formyl derivative $[Fe(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4CHO)]$,[30] which shows a mesophase between 316 K and the melting point (396 K). Similar dynamic behaviour is shown by $[Fe(\eta^5\text{-}C_5H_5)(\eta^5\text{-}C_5H_4CMeO)]$,[30] which undergoes a reversible phase change before melting.

Table 2 Phase transition behaviour and thermodynamic data for $[(\eta^5\text{-}C_5H_5)M][PF_6]$ (M = Co, Fe), $[(\eta^6\text{-}C_6H_6)_2Cr][PF_6]$ and $[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru][PF_6]$

Species	Phase transitions[a,28]	ΔH kJ mol^{-1}
$[(\eta^5\text{-}C_5H_5)_2Fe][PF_6]$	LT → RT at 213.1 K ($P2_1/c \Leftrightarrow P2_1/c$)	1.95
	RT → HT at 347.1 K ($P2_1/c \Leftrightarrow P2_1/c$)	4.50
$[(\eta^5\text{-}C_5H_5)_2Co][PF_6]$	LT → RT at 251.8 K ($P2_1/c \Leftrightarrow P2_1/c$)	1.27
	RT → HT 313.9 K ($P2_1/c \Leftrightarrow P2_1/c$)	3.06
$[(\eta^5\text{-}C_5H_5)(\eta^6\text{-}C_6H_6)Ru][PF_6]$	No RT → LT transition down to 223 K	—
	RT → HT at 332.5 K ($Pna2_1 \Leftrightarrow Pban$)	4.16
$[(\eta^6\text{-}C_6H_6)_2Cr][PF_6]$	No RT → LT transition down to 223 K	—

[a] Differential scanning calorimetry data, heating cycle.

X-Ray powder diffraction of bis-formylferrocene shows that the HT phase retains some degree of crystallinity. After the first heating/cooling cycle the endothermic peak 'moves' from 311 K to *ca*. 308 K indicating the formation of a new phase (RT-2) stable at room temperature. Subsequent cycles of heating and cooling show that the sample reversibly switches between RT-2 and HT without reverting to RT-1. This behaviour suggests that form RT-1 is a kinetic product of the crystallisation process: on heating, the sample undergoes an order → disorder phase transition to the plastic phase HT, which transforms on cooling to the thermodynamically more stable form RT-2. Once RT-2 is formed, RT-1 can no longer be obtained, unless the compound is redissolved and recrystallised. The process is summarised in Scheme 3. It is worth mentioning that on further heating crystalline $[Fe(\eta^5\text{-}C_5H_4CHO)_2]$ above the phase transition temperature, an exothermic peak is observed on the DSC plot at 453 K; this peak was taken as indicative of the occurrence of a polymerisation reaction in the solid state.



Scheme 3 Schematic view of the relationship between the different phases in $[(\eta^5\text{-}C_5H_4CHO)_2Fe]$.

2.5 Polymorphs and weak intermolecular interactions

In previous Sections we have often mentioned intermolecular interactions in association with phase transitions and polymorph formation. Here we discuss a number of illustrative cases in which differences between polymorphs are clearly related to the existence of secondary interactions in the solid state.

The complex $HMn(CO)_5$, one of the first carbonyl hydrides to be structurally characterised by X-ray and neutron diffraction,[31] is known in two polymorphic forms, both monoclinic, called α-$HMn(CO)_5$ and β-$HMn(CO)_5$. In the former, the hydride ligand position could not be located, whereas in the second polymorph a neutron determination was carried out giving an H··H intermolecular distance of 2.292 Å (see Fig. 6). This contact has been investigated by extended Hückel and DFT calculations showing that the (Mn–)H··H(–Mn) interaction can be described as a greatly weakened interatomic H–H bond (a binding energy of *ca.* 5 kJ mol^{-1}).[31] This is in agreement with the observation that dihydrogen bonds involving intramolecular and intermolecular interactions of the M–H··H–X type (X = C, N, O, S) can be weakly attractive in nature, as has been demonstrated by spectroscopic and diffraction experiments and discussed in theoretical studies.[32]

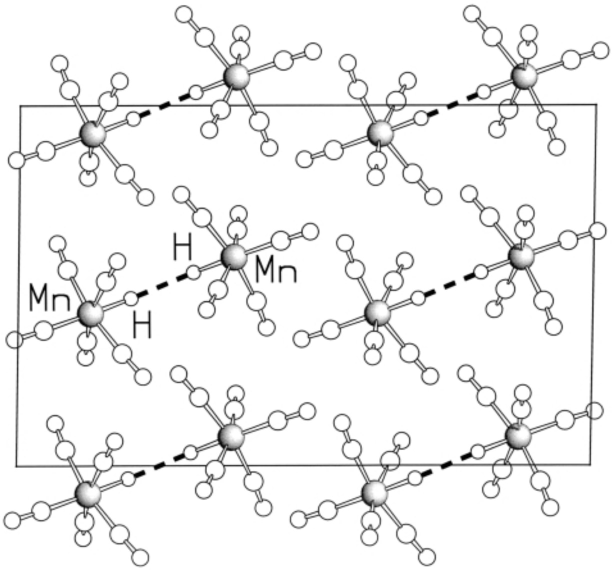


Fig. 6 A layer of molecules in the β-form of crystalline $HMn(CO)_5$ showing how the molecules are joined by H··H interactions.

A related structural situation is shown by $[(\eta^5\text{-}C_5H_5)_2MoH(CO)][(\eta^5\text{-}C_5H_5)Mo(CO)_3]$,[31] which crystallises in two different forms (see Fig. 7). In the monoclinic form the intermolecular (Mo)H··O distances are short, suggesting intermolecular interactions, but in the triclinic form the different orientations of the cations lead to much longer (Mo)H··O distances and bring together neighbouring hydride ligands [H··H = 2.234 Å]. It is worth mentioning that, besides the interactions involving the hydride ligands, there are several C–H··O interactions between cations and anions. Extended Hückel calculations show that in the former case there is an electrostatic interaction between the positively charged hydride and the negatively charged oxygen, while in the H··H dimer the situation parallels that found for the $HMn(CO)_5$ dimer.

3 Inducing pseudo-polymorphs *via* non-solution methods

This section will focus on some examples of *induced* organometallic polymorphism. In particular, we will discuss how

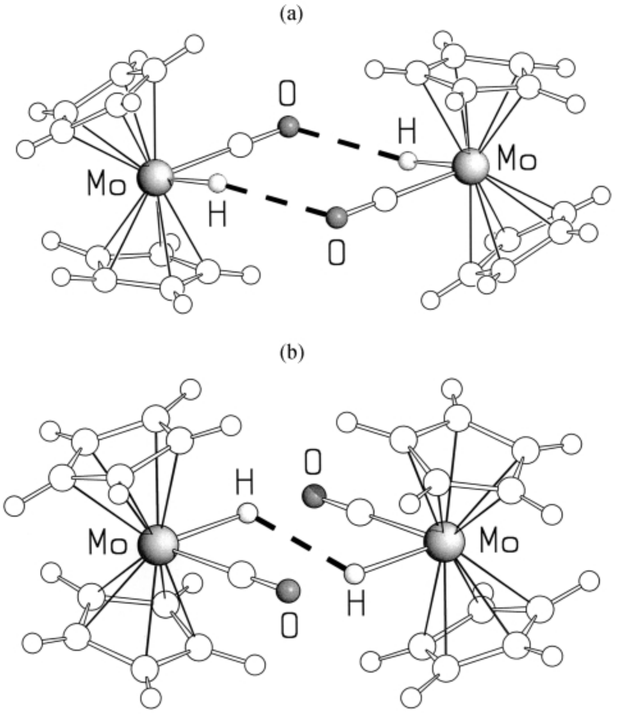


Fig. 7 The monoclinic (a) and triclinic (b) forms of $[(\eta^5\text{-}C_5H_5)_2MoH(CO)][(\eta^5\text{-}C_5H_5)Mo(CO)_3]$.

formation of new crystalline phases may be achieved by mechanical grinding and/or by thermal dehydration in thermogravimetric experiments (TGA) and how crystallisation of these elusive phases may be obtained *via seeding*. An early example of induced crystallisation is that of ferrocene in its eclipsed structure obtained by seeding a solution at low temperature with ruthenocene crystals.[7]

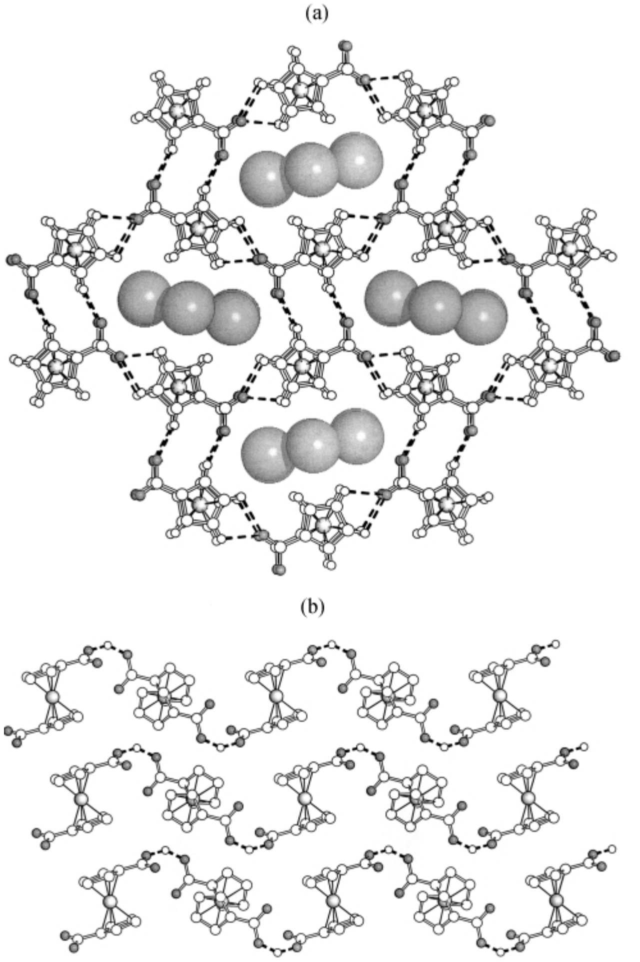
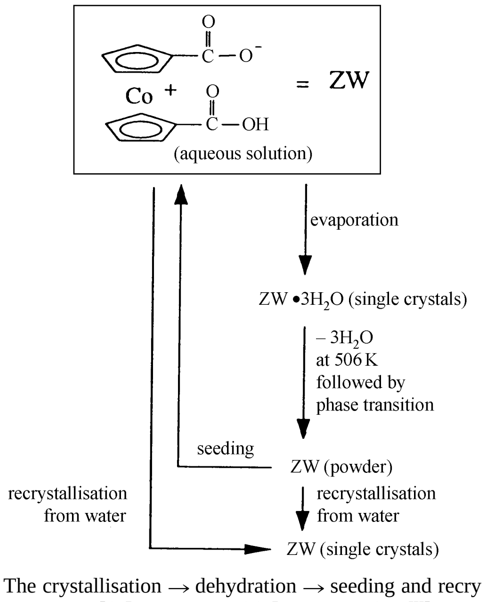


Fig. 8 Comparison of the zwitterion arrangement in crystals of anhydrous $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]$ (a) obtained by *seeding* the starting solution with 'seeds' prepared by step-wise dehydration and subsequent phase transition of the hydrated species $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]\cdot 3H_2O$ (b) (see Scheme 4).

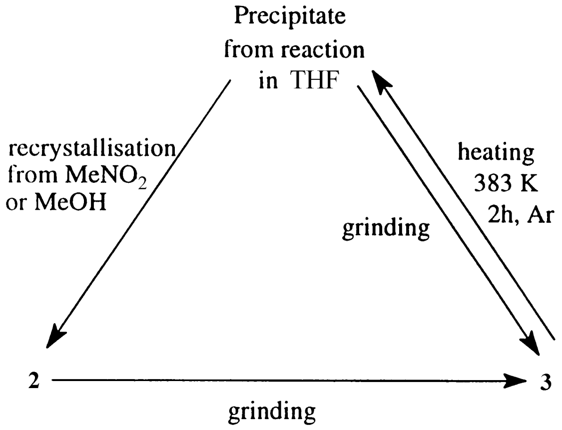


Scheme 4 The crystallisation → dehydration → seeding and recrystallisation of the zwitterion $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]$.

Single crystals of the anhydrous polymorphic modification of the neutral zwitterion $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]$ can be obtained by *seeding* the aqueous solution with 'seeds' prepared by step-wise dehydration and subsequent phase transition of the hydrated species $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]\cdot 3H_2O$ (see Fig. 8).[33] Both anhydrous and hydrated species have been structurally characterised by single crystal and powder diffraction, and the conversion of the initial hydrated product into the anhydrous zwitterion has been monitored by DSC and thermogravimetric analysis (TGA). TGA shows that the hydrated form reversibly releases one water molecule at 378 K, while the loss of the two remaining water molecules occurs at *ca.* 506 K and is immediately followed by a phase transition. Powder diffraction shows that the first dehydration leaves the crystal structure almost unchanged. Most remarkably, crystallisation *from an aqueous solution* of the powder obtained from TGA at 506 K in the presence of *seeds* (a small portion of *the same powder*) leads to the growth of single crystals of the anhydrous species. The whole process is shown in Scheme 4. The structure of $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]$ is based on a one-dimensional network of O–H··O bonded zwitterion molecules (see Fig. 8). Comparison of the calculated and measured powder diffractograms of the anhydrous phase confirms that the powder obtained at 506 K and the single crystals precipitated at room temperature after *seeding* possess the same structure. Importantly, while crystallisation, *in the presence of seeds of the anhydrous form*, leads to isolation of single crystals of the anhydrous material, *in the absence of seeds* the hydrated species is obtained. This latter form can, therefore, be seen as a pseudo-polymorphic modification of $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]$. It seems reasonable to conclude that the anhydrous form is thermodynamically less stable than the hydrated one and can only be obtained by dehydration of $[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Co^{III}]\cdot 3H_2O$ or *via seeding* of the solution, *i.e.* the process is very likely under kinetic control.

A related phenomenon has been observed in the case of the hydrated crystalline material $[(\eta^5\text{-}C_5H_5)_2Co]^+[(\eta^5\text{-}$

$C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Fe]^- \cdot H_2O$.[34] The hydrated form is obtained by simply grinding either the crystalline powder that precipitates from the solvent (THF) on reacting $[(\eta^5\text{-}c_5H_5)_2Co]$ with $[(\eta^5\text{-}C_5H_4COOH)_2Fe]$ or single crystals of the anhydrous salt $[(\eta^5\text{-}C_5H_5)_2Co]^+[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Fe]^-$ obtained by recrystallisation of the same powder from nitromethane. Once $[(\eta^5\text{-}C_5H_5)_2Co]^+[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Fe]^- \cdot H_2O$ has been obtained by grinding, *its single crystals* can be grown from water or nitromethane, while crystals of the anhydrous form are no longer observed. However, on heating at 383 K the hydrated form loses water and reverts to the starting material (see Scheme 5). The process has been investigated by TGA and by powder and single crystal X-ray diffraction. Although the effect of grinding samples (a necessary step for the preparation of samples for powder diffraction experiments) is well known, what appears to be noteworthy in the case of the anhydrous → hydrated transformations is the fact that water molecules can be inserted in a stoichiometric amount into a complex and highly organised crystal edifice without loss of crystallinity or disruption of the anionic organisation. The relationship between polymorph and pseudo-polymorph is shown in Fig. 9.



$\mathbf{2} = [(C_5H_5)_2Co]^+ [(C_5H_4COOH)(C_5H_4COO)Fe]^-$

$\mathbf{3} = [(C_5H_5)_2Co]^+ [(C_5H_4COOH)(C_5H_4COO)Fe]^- \cdot H_2O$

Scheme 5 The crystallisation → grinding → dehydration → seeding and recrystallisation of the hydrated and anhydrous forms of $[(\eta^5\text{-}C_5H_5)_2Co]^+[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Fe]^-$.

The notion that powder grinding, a common method of sample preparation, may lead to solid state transformations and to formation of new polymorphic modifications could be crucial for the success of crystal engineering and solid state chemistry processes. While scientists in the pharmaceutical industry are aware of this phenomenon and of the possible consequences of tableting and other mechanical processing on solid drugs,[35] this awareness is not diffuse in the field of crystal engineering, which still has an essentially academic basis and originates from synthetic chemistry and crystallography rather than from applied research in materials chemistry. However, since crystal engineering reaction products are solids for which routine analytical and spectroscopic laboratory tools are much less useful than in the case of solution chemistry, the utilisation of powder diffraction is, sometimes, the only way to ascertain whether the whole solid material has the same structure as that characterised by single crystal diffraction. Since the crystallisation product may not represent the most stable (thermodynamic) system, any new solid material should be subjected routinely to a DSC run in order to ascertain the possibility of phase transitions. In so doing one may find a way to solve the perpetual kinetic/thermodynamic dilemma of crystal nucleation: '*are my crystals the most stable thermodynamic forms or only those quickest to grow*?'

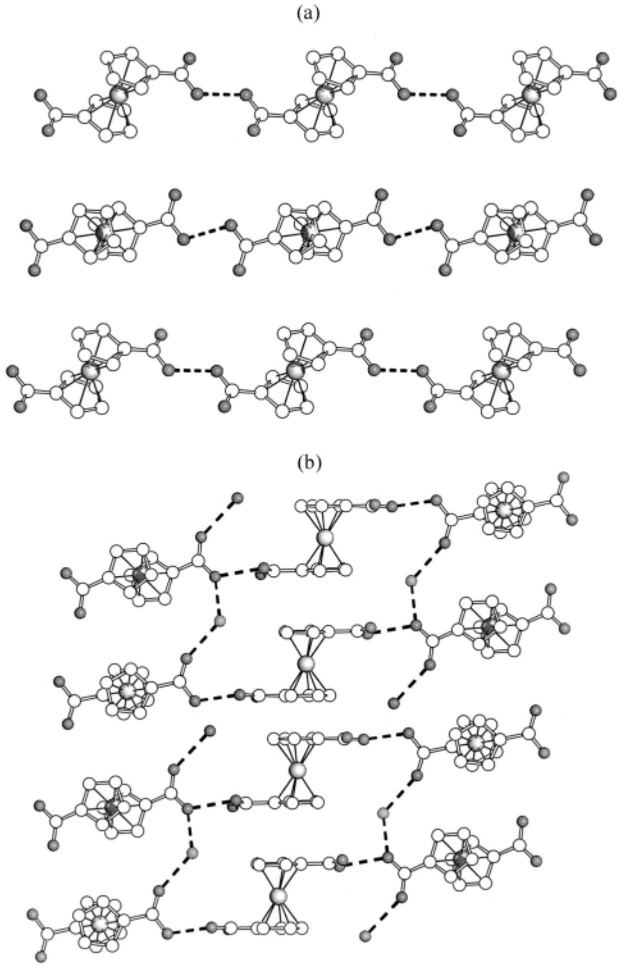
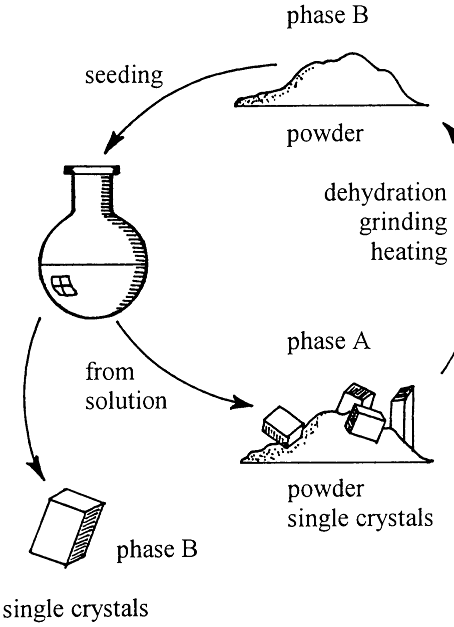


Fig. 9 A comparison of the ion organisation in the anhydrous (a) and hydrated (b) forms of the supramolecular salt $[(\eta^5\text{-}C_5H_5)_2Co]^+[(\eta^5\text{-}C_5H_4COOH)(\eta^5\text{-}C_5H_4COO)Fe]^-$ (see Scheme 5).

Also of some importance is the notion that mechanical stress (and the consequent thermal effect) may achieve quantitative crystal transformations. One may envisage a general approach to the relationship between polymorphs and pseudo-polymorphs. If seeds of the elusive polymorphic modification can be obtained by non-solution methods (*i.e.* mechanical, thermodynamic, perhaps solid state reactions) these can be used to circumvent the kinetic control of the nucleation, allowing growth of less kinetically favoured (hence, very likely, more thermodynamically stable) crystal forms. The basic idea is depicted in the cartoon shown in Scheme 6.

4 Conclusions

In our opinion, polymorphism is one of the most fascinating phenomena of solid state chemistry and crystal engineering. It is a 'difficult' phenomenon, studied for many decades mainly, and separately, in the fields of organic and inorganic chemistry. In spite of the huge efforts of many researchers our knowledge is still embryonic. The relationship between the growth of thermodynamically stable (or metastable) crystalline phases and nucleation of the first crystallites is still mysterious. The development of supramolecular chemistry has shown that vertical divisions of chemistry (organic, inorganic, organometallic) are no longer sufficient to discuss or understand



Scheme 6 Seeds obtained from non-solution methods (*i.e.* mechanical, thermodynamic, perhaps solid state reactions) can be used to nucleate and grow less accessible polymorphic forms.

collective properties and behaviours. On expanding towards solid state organometallic chemistry we may benefit enormously from the vast knowledge accumulated in neighbouring areas of chemistry. In broad terms organometallic compounds share with organic ones the 'periphery', *i.e.* the outer atoms, those that matter most in the formation and stability of the intermolecular interactions, hence in the packing of molecules in the solid state. On the other hand, organometallic and inorganic compounds are often charged species, made of ions, sometimes large polynuclear ions. The presence of ions implies electrostatic interactions that are usually much stronger (but less directional) than van der Waals and hydrogen bonding interactions. As shown in this review, studies of organometallic crystal engineering and polymorphism have to take into account both 'molecularity' and 'ionicity' to appreciate the relationship between crystal cohesion and transformation. Thanks to the work of many groups we begin to understand the formation priorities of intermolecular interactions, and the interplay between directionality and robustness of intermolecular links.

Polymorph 'prediction' for organic molecules is a rapidly developing area of computational research, but despite significant investment it is far from yielding results of wide applicability. Given these difficulties, computational polymorph prediction for organometallics must be regarded as pure witchcraft! The problem of dealing theoretically with organometallic polymorphism is, in fact, complicated by the lack of sufficiently flexible potential parameters for the treatment of metal atoms and by ignorance of the convolution of these parameters with those pertaining to the non-covalent bonding of organometallic molecules in the crystals. Besides, organometallic molecules are generally flexible, hence more easily adaptable in the process of global crystal energy minimisation, offering many opportunities for polymorph formation. This situation calls for more experimental and theoretical work. With this contribution we intended to draw the reader's attention to the opportunities and options (and new challenges) offered by organometallic systems.

Acknowledgements

We have benefited enormously from collaborations with a number of scientists worldwide and from the efforts of many students and visiting scientists at Bologna. Their contribution to the work described in this review is clear from the list of references. All these exchanges have been made possible by a number of funding agencies and bilateral projects (CNR, CRUI, Vigoni, Erasmus, NATO and Ciba-Geigy exchange programs). The most recent work on pseudo-polymorphism has been possible thanks to financial support from MURST (project "Supramolecular Devices"), from the University of Bologna (project "Innovative Materials") and from the University of Sassari. The photograph was taken by our friend Carlo Mealli on the occasion of the 1999 FECHEM meeting in Lisbon. Finally, we would like to acknowledge many years of friendship and scientific interaction with Joel Bernstein; we never found him "too busy" to answer promptly one of our (many) doubts on polymorphism.

6 References

1 W. C. McCrone, in *Polymorphism in Physics and Chemistry of the Organic Solid State*, Eds. D. Fox, M. M. Labes, A. Weissemberg, Interscience: New York, 1965; vol. II, p. 726.
2 J. Bernstein, in *Organic Solid State Chemistry*, Ed. G. R. Desiraju, Elsevier: Amsterdam, 1987, p. 471 and refs. therein.
3 T. L. Threlfall, *Analyst* (*London*), 1995, **120**, 2435.
4 A. Burger, in *Topics in Pharmaceutical Sciences*, Eds. D. D. Breimer, P. Speiser, Elsevier: Amsterdam, 1983, p. 347.
5 (*a*) S. R. Byrn, in *Solid State Chemistry of Drugs*, Academic Press: New York, 1982, p. 79; (*b*) W. H. DeCamp, in *Crystal Growth of Organic Materials*, Eds. A. S. Myerson, D. A. Green, P. Meenan, ACS Proceedings Series, Washington, DC, 1996.
6 J. Dunitz and J. Bernstein, *Acc. Chem. Res.*, 1995, **28**, 193.
7 J. Dunitz, *Acta Crystallogr., Sect. B*, 1995, **51**, 619.
8 J. Bernstein, R. J. Davey and J.-O. Henck, *Angew. Chem., Int. Ed. Engl.*, 1999, **38**, 3440.
9 F. H. Allen and O. Kennard, *Chem. Design Autom. News*, 1993, **8**, 31.
10 D. Braga, *Chem. Rev.*, 1992, **92**, 369.
11 G. R. Desiraju, *Crystal Engineering: The Design of Organic Solids*, Elsevier: Amsterdam, 1989.
12 A. Gavezzotti, *Acc. Chem. Res.*, 1994, **27**, 309.
13 See, for a recent overview: N. Bladgen and R. J. Davey, *Chem. Br.*, 1999, **35**, 44.
14 For a recent overview see: *Crystal Engineering: from Molecules and Crystals to Materials*, Eds. D. Braga, F. Grepioni, A. G. Orpen, Kluwer Academic Publishers: Dordrecht, 1999.
15 D. Braga and F. Grepioni, *Chem. Commun.*, 1996, 571 and references therein.
16 D. Braga and F. Grepioni, *Organometallics*, 1992, **11**, 711 and references therein.
17 References to the original structural papers can be found in: D. Braga and F. Grepioni, *Acc. Chem. Res.*, 1994, **27**, 51.
18 Original reports are $Fe_3(CO)_{12}$: C. H. Wei and L. F. Dahl, *J. Am. Chem. Soc.*, 1969, **91**, 135; $Ru_3(CO)_{12}$: M. R. Churchill, F. J. Hollander and J. P. Hutchinson, *Inorg. Chem.*, 1977, **16**, 2655; $Os_3(CO)_{12}$: M. R. Churchill and B. G. DeBoer, *Inorg. Chem.*, 1977, **16**, 878. Other relevant references can be found in: D. Braga, F. Grepioni, B. F. G. Johnson and J. Farrugia, *J. Chem. Soc., Dalton Trans.*, 1994, 2911.
19 D. Braga, F. Grepioni, B. F. G. Johnson, E. Parisini, M. Martinelli, M. A. Gallop and J. Lewis, *J. Chem. Soc., Dalton Trans.*, 1992, 807 and references therein.
20 Original reports are referenced in: D. Braga, F. Grepioni, J. J. Byrne and M. J. Calhorda, *J. Chem. Soc., Dalton Trans.*, 1995, 3287 for $M_4(CO)_{12}$ (M = Co, Rh, Ir) and in: D. Braga, F. Grepioni, H. Wadepohl, S. Gebert, M. J. Calhorda and L. F. Veiros, *Organometallics*, 1995, **14**, 24 for $[(C_5H_5)_3M_3(CO)_3]$ (M = Co, Rh and Ir).
21 D. Braga, F. Grepioni, E. Tedesco and A. G. Orpen, *J. Chem. Soc., Dalton Trans.*, 1995, 1215 and references therein.

22 Original reports are referenced in: D. Braga, F. Grepioni, E. Tedesco, M. J. Calhorda and P. E. M. Lopes, *New J. Chem.*, 1999, 219.

23 D. Braga and F. Grepioni, in *Topics in Organometallic Chemistry*, Eds. J. M. Brown, P. Hofmann, Springer Verlag: Berlin, 1999, Vol. 4, p. 48.

24 F. Takusagawa and T. F. Koetzle, *Acta Crystallogr., Sect. B*, 1979, **35**, 2888.

25 See for example: B. F. G. Johnson, *J. Chem. Soc., Dalton Trans.*, 1997, 1473 and references therein.

26 L. Farrugia, A. L. Gillon, D. Braga and F. Grepioni, *Organometallics*, 1999, **18**, 5022 and references therein.

27 J. D. Dunitz, in *Perspectives in Supramolecular Chemistry. The Crystal as a Supramolecular Entity*, Ed. G. R. Desiraju, Wiley: Chichester, 1996.

28 F. Grepioni, G. Cojazzi, S. M. Draper, N. Scully and D. Braga, *Organometallics*, 1998, **17**, 296.

29 F. Grepioni, G. Cojazzi, D. Braga, E. Marseglia, L. Scaccianoce and B. F. G. Johnson, *J. Chem. Soc., Dalton Trans.*, 1999, 553.

30 D. Braga, F. Paganelli, E. Tagliavini, S. Casolari, G. Cojazzi and F. Grepioni, *Organometallics*, 1999, **18**, 4191 and references therein.

31 For the neutron study see: S. J. La Placa, W. C. Hamilton, J. A. Ibers and A. Davison, *Inorg. Chem.*, 1969, **8**, 1928; for the computational and CSD study see: D. Braga, P. De Leonardis, F. Grepioni, E. Tedesco and M. J. Calhorda, *Inorg. Chem.*, 1998, **37**, 3337.

32 For an overview of di-hydrogen bonding see: R. H. Crabtree, P. E. M. Siegbahn, O. Eisenstein, A. L. Rheingold and T. F. Koetzle, *Acc. Chem. Res.*, 1996, **29**, 348.

33 D. Braga, L. Maini, L. M. Polito and F. Grepioni, *Chem. Commun.*, 1999, 1949.

34 D. Braga, F. Grepioni and L. Maini, *Chem. Commun.*, 1999, 937.

35 See, for example: J. J. Gerber, M. R. Caira and A. P. Lötter, *J. Crystallogr. Spectrosc. Res.*, 1993, **23**, 863.