Isolation and characterisation of stereoisomers in di- and tri-nuclear complexes

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A number of synthetic methodologies have recently been developed for polymetallic supramolecular assemblies, commonly without consideration of the stereochemistry of the component octahedral metal centres. This review discusses stereochemical aspects of ligand-bridged di- and tri-nuclear complexes, with an emphasis on those involving ruthenium(II) octahedral metal centres coordinated to bidentate *N*-heterocyclic ligands. It examines recent studies devoted to the isolation of individual stereoisomers of such complexes using both stereoselective synthetic procedures through precursors with pre-determined chiralities and/or chromatographic techniques. The characterisation of the stereoisomers is also addressed.

1 Introduction

In recent years, a number of synthetic methodologies have been developed[1] for polymetallic supramolecular assemblies which may have considerable potential as the basis of materials designed for use in photochemical molecular devices.[2] Because of their favourable photophysical and redox characteristics,[3] d^6 transition metal centres (*e.g.* Ru^{II}, Os^{II}, Re^{I}) coordinated to polypyridyl ligands have been of particular interest as the building blocks for such assemblies.

However, in contrast to the development of molecular assemblies in organic chemistry where there was a prior understanding of the nature of the tetrahedral carbon atom, the present advances in inorganic supramolecules have taken place without suitable methodologies to control the stereochemistry at the component octahedral metal centres. This is particularly true where bidentate ligands are involved. However, such ligands are important as they extend the three-dimensionality of resultant polynuclear species, whereas the involvement of tridentate ligands tends to impose chain-like characteristics on the structures. The stereochemical factor should be of considerable importance as the spatial relationship of the components influences the nature of intramolecular electron and energy transfer processes within the assemblies.[4–7] Additionally, the NMR spectra of the oligomeric assemblies are complicated and are different for each stereoisomer (other than enantiomers): consequently, since isolated complexes have generally been isomeric mixtures, characterisation by this technique has been extremely difficult because the spectra were not interpretable. Crystals appropriate for structural studies of such assemblies are notoriously difficult to obtain.

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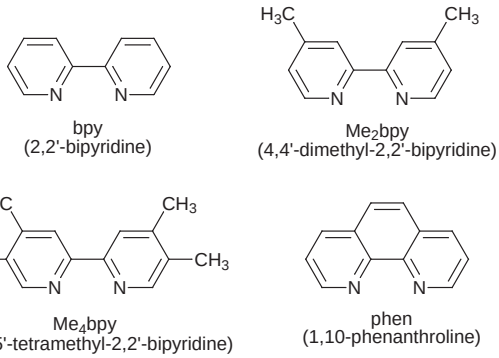
2 Isomers of dinuclear complexes

2.1 Diastereoisomers

Ligand-bridged dinuclear species represent the simplest examples of the assemblies. Where the individual centres are tris(bidentate) in nature, each may inherently possess right- or left-handed chirality (designated Δ or Λ respectively). In principle, a dinuclear species may therefore exist in two diastereoisomeric forms—$\Delta\Delta/\Lambda\Lambda$ or $\Delta\Lambda/\Lambda\Delta$—and where the bridge is relatively rigid, stereoisomerism has a profound effect on shape and on the electronic interactions within the molecule. In cases where the bridge is not rigid and there is free rotation within the link between the two metal centres, the differences may not be so significant, and such species are not considered in any detail in this review.

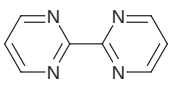
Terminal Ligands



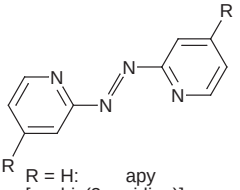
The most fundamental example of the genre is $[\{M(pp)_2\}_2(\mu\text{-}BL)]^{n+}$ [where pp is a symmetrical bidentate ligand (C_{2v} point group symmetry) such as 2,2′-bipyridine (bpy), and BL is a symmetrical (C_{2v}) bridging ligand such as 2,2′-bipyrimidine, bpm]. In this case there are three possible stereoisomers—two diastereoisomers [*meso* (point group symmetry C_{2h}) and *rac* (point group symmetry D_2)], with the latter comprising two enantiomeric forms (Fig. 1).

The terminal bidentate polypyridyl ligands 'above' and 'below' the plane of the bridging ligand bear a significantly different relationship in the *rac* and *meso* diastereoisomers. For the complexes where the axes of the 'bites' of the two bidentate ligating moieties of the bridge (BL) are linear (*e.g.* bpm) or have a stepped-parallel relationship (*e.g.* 2,5-dpp or apy), the terminal polypyridyl ligands 'above' and 'below' the plane of the bridging ligand are approximately parallel in the *rac* ($\Delta\Delta/\Lambda\Lambda$) form [Fig. 2(B)], whereas they are orthogonal in the *meso* ($\Delta\Lambda/\Lambda\Delta$) stereoisomer [Fig. 2(A)].[8–10] Fig. 2 shows the view

Bridging Ligands

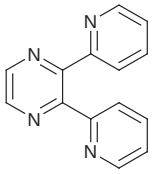


bpm
(2,2'-bipyrimidine)

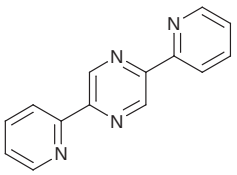


R = H: apy
[azobis(2-pyridine)]

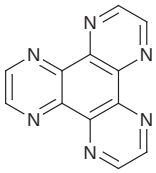
R = CH_3: mapy
[azobis(4-methyl-2-pyridine)]



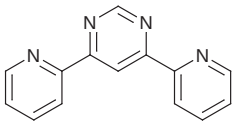
2,3-dpp
[2,3-bis(2-pyridyl)pyrazine]



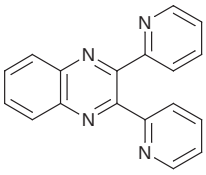
2,5-dpp
[2,5-bis(2-pyridyl)pyrazine]



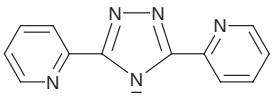
HAT
(1,4,5,8,9,12-hexaazatriphenylene)



4,6-dppm
[4,6-bis(2-pyridyl)pyrimidine]



dpq
[2,3-bis(2-pyridyl)quinoxaline]



bpt^-
[3,5-bis(2-pyridyl)-1,2,4-triazolate anion]

from above the bridging ligand (bpm) in the complex $[\{Ru(bpy)_2\}_2(\mu\text{-bpm})]^{4+}$.

On the other hand, if the relationship of the axes of the two 'bites' are angular (*e.g.* the 'unsymmetrical' bridging ligands 2,3-dpp, 4,6-dppm, HAT), the above description is reversed, with the terminal rings above the plane of the bridge being more appropriately described as approximately parallel and orthogonal for the *meso* [Fig. 3(B)] and *rac* [Fig. 3(A)] diastereoisomers (respectively) in the complex $[\{Ru(bpy)_2\}_2(\mu\text{-HAT})]^{4+}$.

When each metal centre of the dinuclear species has two equivalent ligands but the two metal centres are no longer identical, as in the homometallic case $[\{M(pp)_2\}\{M(pp')_2\}(\mu\text{-BL})]^{n+}$ ($pp \neq pp'$) or the heterometallic cases $[\{M(pp)_2\}\{M'(pp)_2\}(\mu\text{-BL})]^{n+}$ and $[\{M(pp)_2\}\{M'(pp')_2\}(\mu\text{-BL})]^{n+}$, then the $\Delta\Lambda$ and $\Lambda\Delta$ forms will constitute an enantiomeric pair. In all three systems, the point group symmetries of both diastereoisomers will be C_2.

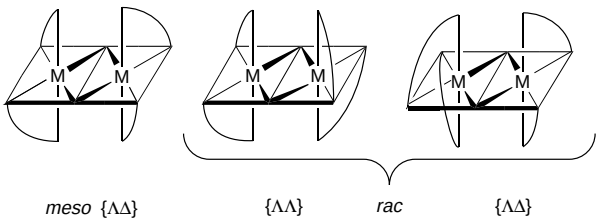


Fig. 1 Stereoisomeric forms of $[\{M(pp)_2\}_2(\mu\text{-BL})]^{n+}$

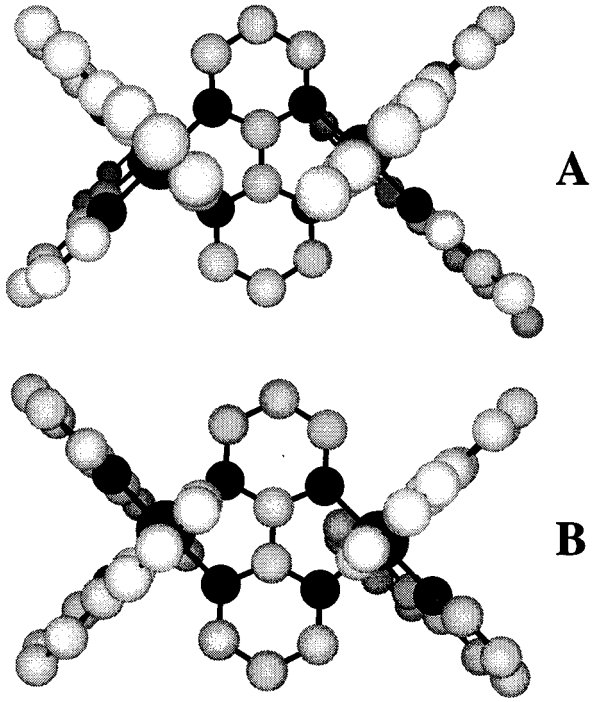


Fig. 2 CHEM3D representations of the *meso* ($\Lambda\Delta$; A) and *rac* ($\Delta\Delta$; B) diastereoisomers of $[\{Ru(bpy)_2\}_2(\mu\text{-bpm})]^{4+}$ (hydrogen atoms are omitted for clarity)

There are limited examples of complexes in the above categories where individual stereoisomers have actually been separated. Hua and von Zelewsky[9,11] utilised the complexes $[Ru(phen)_2(py)_2]^{2+}$ and $[Ru(bpy)_2(py)_2]^{2+}$ [conveniently resolved by conventional diastereoisomer formation using the chiral arsenyl-(+)-tartrate and *O,O'*-dibenzoyltartrate anions, respectively], which they established to undergo stereoretentive substitution of the two monodentate pyridine ligands. These chiral precursors were used to synthesise the dinuclear species

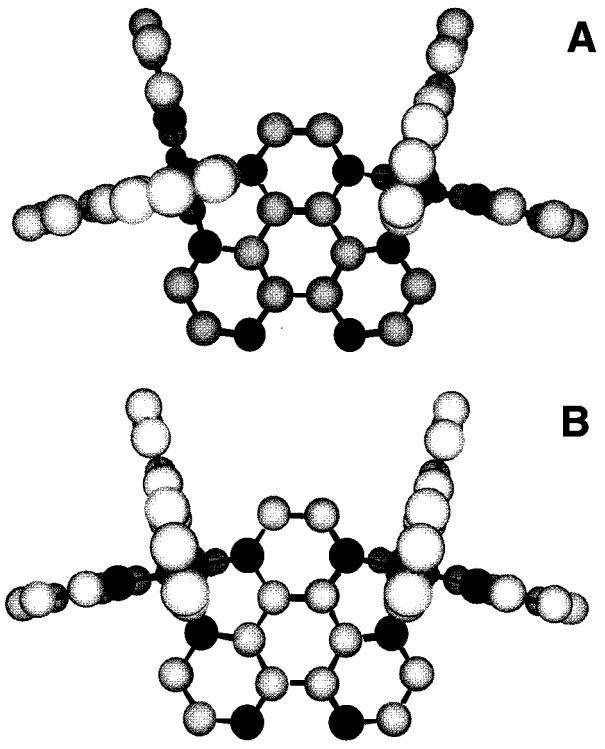


Fig. 3 CHEM3D representations of diastereoisomers of $[\{Ru(bpy)_2\}_2(\mu\text{-HAT})]^{4+}$: (A) *rac* ($\Delta\Delta$; point group symmetry C_2) and (B) *meso* ($\Lambda\Delta$; point group symmetry C_s)

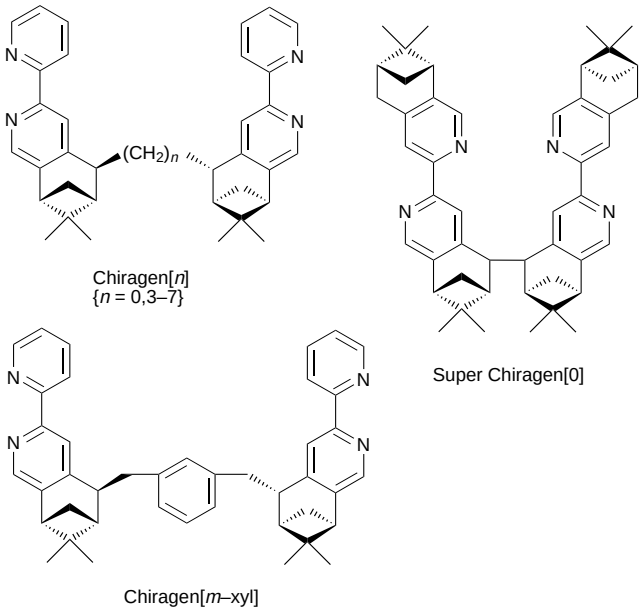
$[\{Ru(pp)_2\}_2(\mu\text{-BL})]^{4+}$ [pp = bpy or phen; BL = bridging ligands 2,2-bipyrimidine (bpm), 2,5-bis(2-pyridyl)pyrazine (2,5-dpp) or 4,6-bis(2-pyridyl)pyrimidine (4,6-dppm)] with predetermined stereochemistry (*i.e.* ΔΛ, ΔΔ or ΛΛ). The methodology has also been used for analogous dinuclear complexes involving the bridging ligands 2,3-bis(2-pyridyl)-pyrazine (2,3-dpp) and its fused analogue pyrazino[2,3-*f*]-[4,7]phenanthroline (ppz).[12]

In studies in our own laboratory, we established the use of chiral $[Ru(pp)_2(CO)_2]^{2+}$ as a precursor for the syntheses of individual stereoisomers of the dinuclear complex $[\{Ru(phen)_2\}\{Ru(Me_4bpy)_2\}(\mu\text{-bpm})]^{4+}$.[13] We have also extended the technique of Hua and von Zelewsky[9,11] by the utilisation of resolved hetereoleptic bis(pyridine) species $\{[Ru(pp)(pp')(py)_2]^{2+}$ to obtain individual stereoisomers of $[\{Ru(phen)(Me_4bpy)\}_2(\mu\text{-bpm})]^{4+}$.[14]

Importantly, we have also used cation exchange chromatographic methods to separate the diastereoisomers of the dinuclear species $[\{Ru(bpy)_2\}\{Ru(phen)_2\}(\mu\text{-bpm})]^{4+}$, $[\{Ru(bpy)_2\}\{Ru(phen)_2\}\{\mu\text{-(2,3-dpp)}\}]^{4+}$, $[\{Ru(phen)_2\}\{Ru(Me_4bpy)_2\}(\mu\text{-bpm})]^{4+}$, $[\{Ru(bpy)_2\}\{Ru(Me_4bpy)_2\}(\mu\text{-bpm})]^{4+}$, $[\{Ru(phen)_2\}\{Os(bpy)_2\}(\mu\text{-bpm})]^{4+}$, and $[\{Ru(Me_4bpy)_2\}\{Os(bpy)_2\}(\mu\text{-bpm})]^{4+}$,[8] $[\{Ru(bpy)_2)\}_2(\mu\text{-apy})]^{4+}$, $[\{Ru(Me_2bpy)_2\}_2(\mu\text{-apy})]^{4+}$, $[\{Ru(bpy)_2\}_2(\mu\text{-mapy})]^{4+}$, $[\{Ru(Me_2bpy)_2\}_2(\mu\text{-mapy})]^{4+}$, and $[\{Ru(bpy)_2\}\{Ru(Me_2bpy)_2\}(\mu\text{-mapy})]^{4+}$.[4]

The combination of these stereoselective synthetic techniques and chromatographic procedures provides a significant advance in the access to stereoisomeric forms of dinuclear complexes and oligomers of higher nuclearity. We have used such methodologies to isolate all stereoisomers of the dinuclear species $[\{Ru(bpy)_2\}_2(\mu\text{-HAT})]^{4+}$ (Fig. 3) and $[\{Ru(phen)_2\}_2(\mu\text{-HAT})]^{4+}$,[6] and $[\{Ru(bpy)_2\}\{Ru(phen)_2\}(\mu\text{-HAT})]^{4+}$:[15] examples of studies of trinuclear species are given below.

There have been a number of other approaches to the isolation of individual stereoisomeric forms of ligand-bridged dinuclear species. von Zelewsky and co-workers have reported the use of ligands ('chiragens') which impose a particular stereochemistry on the monomer precursors ('stereospecificity').[16,17]



A number of studies have reported utilising condensation reactions of chiral monomers containing the 1,10-phenanthroline-5,6-dione ligand, *e.g.* $[Ru(phen)_2(1,10\text{-phenanthroline-5,6-dione})]^{2+}$,[18] as the precursor to form bridged complexes of predetermined stereochemistry.[19–22]

Tor and co-workers[23] have reported the use of the Hua and von Zelewsky precursor $\Delta/\Lambda\text{-}[Ru(phen)_2(py)_2]^{2+}$ to produce chiral complexes of functionalised phen ligands,[9,11] which may be subsequently linked to form individually the ΔΔ, ΛΛ and ΔΛ stereoisomers of an alkyne-bridged dinuclear species. These researchers also reported the use of analogous methods to obtain the ΛΛΛ and ΔΛΔ diastereoisomers of trinuclear species.[23]

There are no reports of the isolation of the individual diastereoisomers of dinuclear species involving 'unsymmetrical' bridging ligands, although there are examples—such as the case involving 3,5-bis(2-pyridyl)-1,2,4-triazolate anion (bpt^-)—where the coordination isomers of the complex[24] $[\{Ru(bpy)_2\}\{Ru(phen)_2\}(\mu\text{-bpt})]^{3+}$ and[25] $[\{Ru(bpy)_2\}\{Os(bpy)_2\}(\mu\text{-bpy})]^{3+}$ have been synthesised.

In almost all the dinuclear systems listed above where separation of diastereoisomeric forms was achieved (or the two forms quantified in a mixture), the ratios of their proportions were close to 1 : 1. One notable exception is the species $[\{Ru(bpy)_2\}_2(\mu\text{-mapy})]^{4+}$ where the *meso : rac* ratio was 3.8 : 1.[4] In the mapy bridging ligand, the two bidentate 'bites' have a stepped-parallel relationship, and the offset position of the metal centres places the 'above plane' ligands almost coplanar in the ΔΔ/ΛΛ (*rac*) isomer (Fig. 4). The preference for the *meso* diastereoisomer may arise from steric factors, as examination of models reveals possible inter-ligand interactions within the *rac* form.

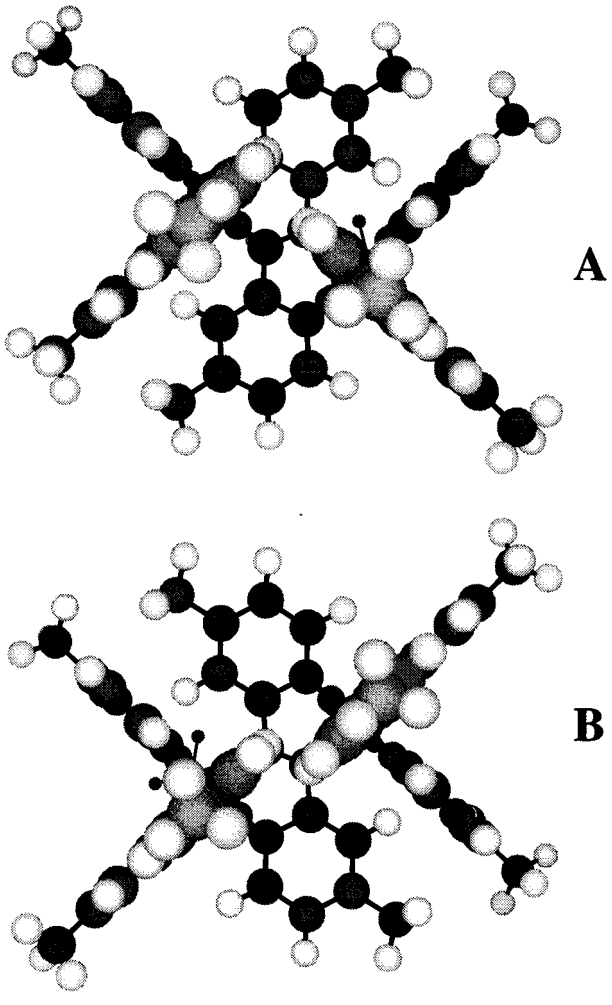


Fig. 4 CHEM3D representations of the (A) *meso* (ΔΛ) and (B) *rac* (ΔΔ) diastereoisomeric forms of $[\{Ru(Me_2bpy)_2\}_2(\mu\text{-mapy})]^{4+}$ (ref. 4)

2.2 Enantiomers

The chromatographic technique may also be used to chirally resolve the enantiomers that comprise the *rac* diastereoisomer in these species, as reported for the complexes $[\{Ru(bpy)_2\}_2(\mu\text{-}$

bpm)]$^{4+}$,[10] [{Ru(pp)$_2$}$_2$(μ-HAT)]$^{4+}$ (pp = bpy, phen)[6] and [{Ru(bpy)$_2$}{Ru(phen)$_2$}(μ-HAT)]$^{4+}$.[15] The chromatographic resolution of the ΔΔΔ and ΛΛΛ forms has also been achieved for the trinuclear species [{Ru(pp)$_2$}$_3$(μ-HAT)]$^{6+}$,[6] [{Ru(bpy)$_2$}$_2${Os(bpy)$_2$}(μ-HAT)]$^{6+}$ and [{Ru(phen)$_2$}{Ru(bpy)$_2$}{Ru(Me$_2$bpy)$_2$}(μ-HAT)]$^{6+}$.[15]

2.3 Geometrical isomers

The presence of more varied combinations of terminal ligands—and the use of unsymmetrical terminal and bridging ligands—leads to situations of increasing complexity. If the metal centres are identical but contain two different terminal ligands {*e.g.* [{Ru(pp)(pp′)}$_2$(μ-BL)]$^{n+}$} then there will still be two diastereoisomeric forms, with each now having two geometrical isomers (*cis* and *trans*), as shown in Fig. 5.

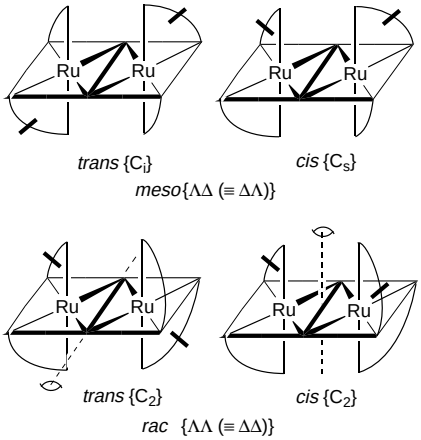


Fig. 5 Schematic representation of the geometrical isomers of the diastereoisomeric forms of [{Ru(pp)(pp′)}$_2$(μ-BL)]$^{n+}$ (C_2 axes are shown)[14]

For the dinuclear complex [{Ru(phen)(Me$_4$bpy)}$_2$(μ-HAT)]$^{4+}$, the diastereoisomeric forms [*meso* (ΔΛ) and *rac* (ΔΔ/ΛΛ)] were either separated by cation exchange chromatography, or the individual forms (ΔΛ, ΔΔ and ΛΛ) synthesised stereoselectively by reaction of appropriate chirally resolved forms of [{Ru(phen)(Me$_4$bpy)}$_2$(py)$_2$]$^{2+}$ and [{Ru(phen)(Me$_4$bpy)}(bpm)]$^{2+}$.[14] Each diastereoisomer was chromatographically separated into its two geometrical forms, which were readily assigned by NMR techniques on the basis of symmetry.

The final scenario in this series of dinuclear complexes involving symmetrical bridging ligands is the situation in which there are unsymmetrical terminal ligands coordinated to the metal centres involved. For example, with a bidentate ligand A–B, then each Ru(A–B)$_2$(BL) moiety may exist in three geometric forms (each of which may be chiral)—accordingly there will be six geometrical forms of each of the two diastereoisomers. Isolation of all forms would indeed be a challenge!

2.4 Conformational isomers

It is also noted that in cases where there is some limited movement within the ligand bridge, conformational isomerism may also be observed. In dinuclear complexes involving 2,3-bis(2-pyridyl)pyrazine as the bridge, the steric interaction of the two protons attached at the 3-positions of the respective pyridine rings imposes non-planarity on the two α,α′-diimine coordinating moieties. This effect has been described in a monomeric complex of a closely related analogue 2,3-bis(2-pyridyl)quinoxaline (dpq).[26]

In our ^{1}H NMR characterisation of the two diastereoisomers of the dinuclear complex [{Ru(bpy)$_2$}{Ru(phen)$_2$}{μ-(2,3-dpp)}]$^{4+}$,[8,27] a broadening of some of the resonances was observed in the aromatic region of the spectra of the two isomers at room temperature. On raising the temperature a sharpening of the resonances occurred, whereas at low temperatures the resonances not only sharpened but both spectra became considerably more complex (Fig. 6). It is apparent that in these

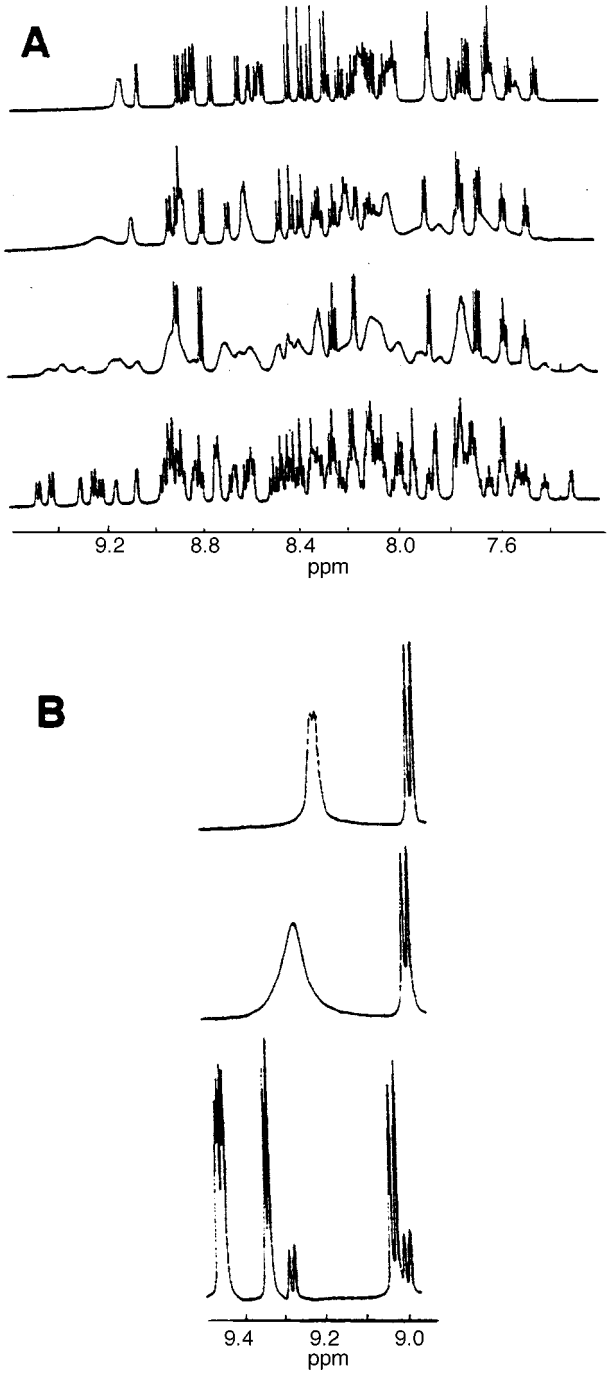


Fig. 6 ^{1}H NMR spectra (aromatic region; 300 MHz; [^{2}H$_6$]acetone solvent) of diastereoisomers of [{Ru(bpy)$_2$}{Ru(phen)$_2$}{μ-(2,3-dpp)}]$^{4+}$ at different temperatures: (A) *meso*, at 45 (top), 10, −10, −50 °C (bottom); (B) *rac*, at 45 (top), 25, −50 °C (bottom)

cases there are conformational isomers which interconvert at room temperature on a time-scale comparable to that of the NMR experiment. At higher temperatures the interconversion becomes more rapid so that the spectrum for each diastereoisomer corresponds to an average conformation. At low temperatures, separate spectra are observed for the two conformations. For this bridging ligand, the two conformations can be assumed to correspond to the two possible skew dispositions of the two α,α′-diimine ligating moieties either side of the mutually planar arrangement (Fig. 7). Because of this

skew relationship the two conformations of the 2,3-dpp ligand are chiral, so that the conformers are in fact diastereoisomeric!

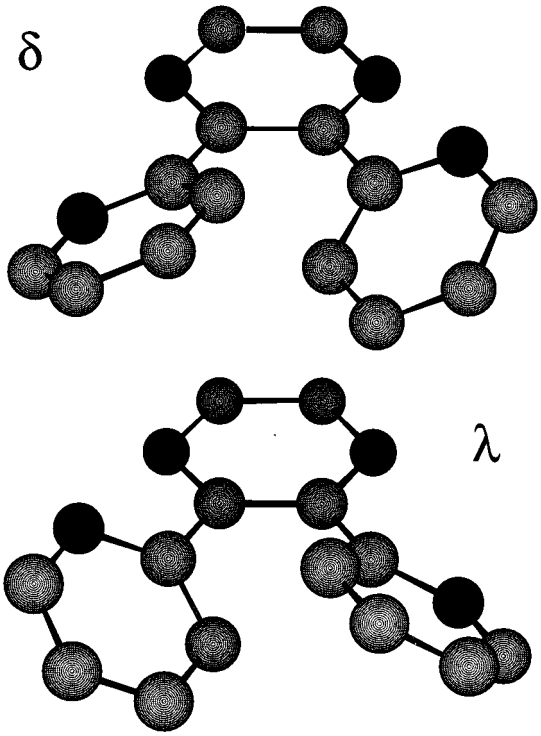


Fig. 7 Conformations of the 2,3-dpp ligand. (Absolute configurations are based on the orientation of the two skew lines[37] generated by the two coordinating N–N moieties.)

It is interesting that in the *meso* diastereoisomer the two conformers are in approximately equal proportions, whereas in the *rac* form they appear in a *ca.* 4 : 1 ratio, perhaps as a consequence of steric interactions.

3 Isomers of trinuclear complexes

There are a very limited number of examples of the isolation of stereoisomeric trinuclear complexes. Two diastereoisomers of an alkyne-bridged trinuclear species have been isolated by Tor and co-workers using chiral precursors, as described earlier.[23] Lehn and co-workers have also reported the isolation of the homochiral forms (ΔΔΔ and ΛΛΛ) of two trinuclear complexes,[28] using the appropriate chiral form of [Ru(phen)$_2$(py)$_2$]$^{2+}$ as precursor,[9,11] and individual diastereoisomeric forms of trinuclear complexes have been obtained which involve a 'chiragen' bridging ligand {chiragen[bpy]}.[17]

Our own methodologies (outlined above) may be extended to higher oligonuclear species. For example, the ligand 1,4,5,8,9,12-hexaazatriphenylene (HAT) may bridge between three metal centres, and we have used a combination of the stereoselective synthetic techniques and chromatographic procedures to isolate the stereoisomeric forms of the homometallic trinuclear complexes [{Ru(bpy)$_2$}$_3$(μ-HAT)]$^{6+}$ and [{Ru(phen)$_2$}$_3$(μ-HAT)]$^{6+}$ (Fig. 8).[6] The techniques may be applied to realise all the stereoisomers of the heterometallic trinuclear species [{Ru(bpy)$_2$}$_2${Os(bpy)$_2$}(μ-HAT)]$^{6+}$ (Fig. 9),[15,29] and the diastereoisomeric forms of homometallic heteroleptic trinuclear species [{Ru(phen)$_2$}{Ru(bpy)$_2$}{Ru(Me$_2$bpy)$_2$}(μ-HAT)]$^{6+}$.[15]

In the chromatographic procedures (discussed below), the separation of diastereoisomers of the various systems is observed to be more efficient than the separation of enantiomeric forms of the diastereoisomers. Accordingly, the reaction of one stereoisomeric form of a dinuclear species (*e.g.* ΔΔ-[{Ru(pp)$_2$}$_2$(μ-HAT)]$^{4+}$) with *rac*-[Ru(pp)$_2$Cl$_2$] results in the diastereoisomeric mixture ΔΔΔ/ΔΔΛ which may readily be separated. To give an example of the methodology, the scheme in Fig. 10 shows the sequence used for the isolation of the stereoisomers of the heterometallic trinuclear species [{Ru(bpy)$_2$}$_2${Os(bpy)$_2$}(μ-HAT)]$^{6+}$.[15,29]

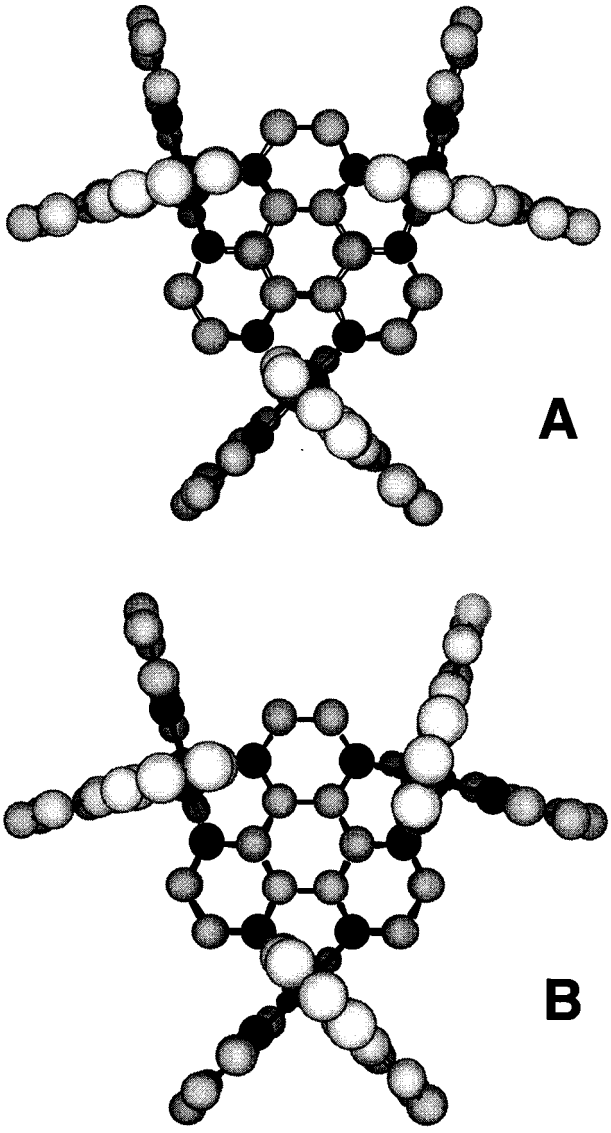


Fig. 8 CHEM3D representation of (A) heterochiral ($\Delta^2\Lambda$) and (B) homochiral Δ^3 ($\equiv\Lambda^3$)} diastereoisomeric forms of [{Ru(bpy)$_2$}$_3$(μ-HAT)]$^{6+}$[6]

The general strategy can be extended to the isolation of stereoisomers of other oligonuclear assemblies involving different terminal and bridging ligands.

4 NMR characterisation of stereoisomers

As noted above, the NMR spectra of the oligomeric assemblies are complex and they are different for each diastereoisomer/geometrical isomer. Until the isolation of individual stereoisomeric forms of such species, the influence on the spectra of electronic effects and magnetic anisotropic interactions between the various terminal and bridging ligands had not been elucidated. For a number of ligand-bridged dinuclear[4,6,9,15] and trinuclear species,[6,15] detailed NMR studies and assignment of individual proton resonances have been undertaken, allowing an assessment of such factors.

To illustrate the point, an example is taken of two trinuclear complexes—*viz.* the homometallic homoleptic complex [{Ru(bpy)$_2$}$_3$(μ-HAT)]$^{6+}$ and its heterometallic analogue [{Ru-

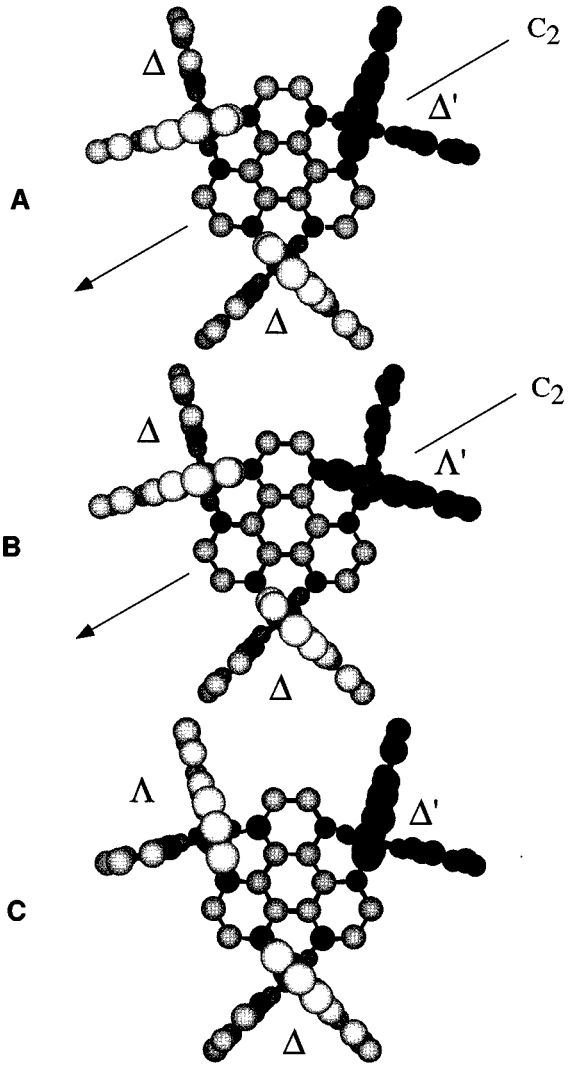


Fig. 9 CHEM3D representations of the diastereoisomeric forms of $[\{Ru(bpy)_2\}_2\{Os(bpy)_2\}(\mu\text{-HAT})]^{6+}$; ΔΔΔ′/ΛΛΛ′ (A), ΔΔΛ′/ΛΛΔ′ (B) and ΛΔΛ′/ΔΛΔ′ (C). {Hydrogen atoms omitted for clarity; bpy rings about Os centre are darkened to allow identification.}[15,29]

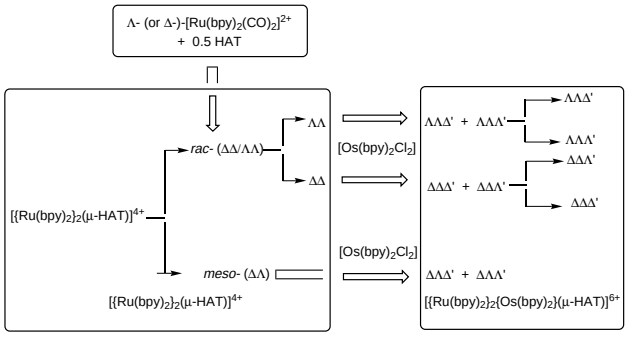


Fig. 10 Synthetic scheme for stereoisomers of $[\{Ru(bpy)_2\}_2\{Os(bpy)_2\}(\mu\text{-HAT})]^{6+}$. (Chromatographic procedures are indicated by single arrows, synthetic procedures by double arrows, and the prime denotes chirality which refers to the osmium centre.)[15,29]

$(bpy)_2\}_2\{Os(bpy)_2\}(\mu\text{-HAT})]^{6+}$. The two diastereoisomers of the Ru_3 species (Fig. 8) have the point group symmetries D_3 (homochiral, Δ^3/Λ^3) and C_2 (heterochiral, $\Delta^2\Lambda/\Lambda^2\Delta$),[6] which give rise to different numbers of inequivalent proton resonances in the ^{1}H NMR spectra. Full assignment of these signals and determination of the relative connectivities can be made using ^{1}H-COSY, NOE-difference spectra and selective decoupling experiments. In particular, the resonances of the H6 (bpy) protons (compared with the H3 protons, for example) show marked differences in chemical shifts depending upon the environment. Since the proton in the H6 position points directly towards the aromatic ring of an adjacent ligand (bpy or HAT), the relative degrees of ring anisotropy (current) experienced will vary considerably. Such effects allow, in conjuction with NOE-difference spectra, the assignment of the positioning of the pyridine rings relative to one another. The connectivity within the rings is established by ^{1}H-COSY spectra. (The assignments are described in detail in the literature for the analogous phen species, but the bpy complexes have been similarly characterised[6]).

For the three diastereoisomeric forms of the analogous heterometallic complex $[\{Ru(bpy)_2\}_2\{Os(bpy)_2\}(\mu\text{-HAT})]^{6+}$ (Fig. 9), the point group symmetries are lowered as the metal centres are no longer identical {*viz.* both the ΔΔΔ′/ΛΛΛ′ [Fig. 9(A)] and ΔΔΛ′/ΛΛΔ′ [Fig. 9(B)] diastereoisomers possess C_2 symmetry, and the ΔΛΛ′/ΛΔΔ′ [Fig. 9(C)] possesses C_1}.[15,29] The spectra are consequently more complex than those of the homonuclear species, to the extent that coincidental equivalences of certain resonances may render assignment of the chemical shifts to individual proton environments ambiguous. Nevetheless, by use of ^{1}H NMR spectroscopic techniques mentioned earlier, as well as ^{1}H-NOESY and ^{1}H-TOCSY experiments, in combination with the symmetry differences and comparisons with the known assignments for the homometallic analogues, a definitive characterisation of the diastereoisomers may be made.[15] These procedures have been extended to the characterisation by NMR techniques of the four diastereoisomers of the homometallic heteroleptic trinuclear species $[\{Ru(bpy)_2\}\{Ru(Me_2bpy)_2\}\{Ru(phen)_2\}(\mu\text{-HAT})]^{6+}$,[15] for each of which there are 54 magnetically non-equivalent proton resonances! The ^{1}H NMR spectra of this sequence of homochiral trinuclear species (ΔΔΔ-Ru_3, -Ru_2Os and -RuRu′Ru″) are presented in Fig. 11 to show the increasing complexity as the symmetry is lowered.

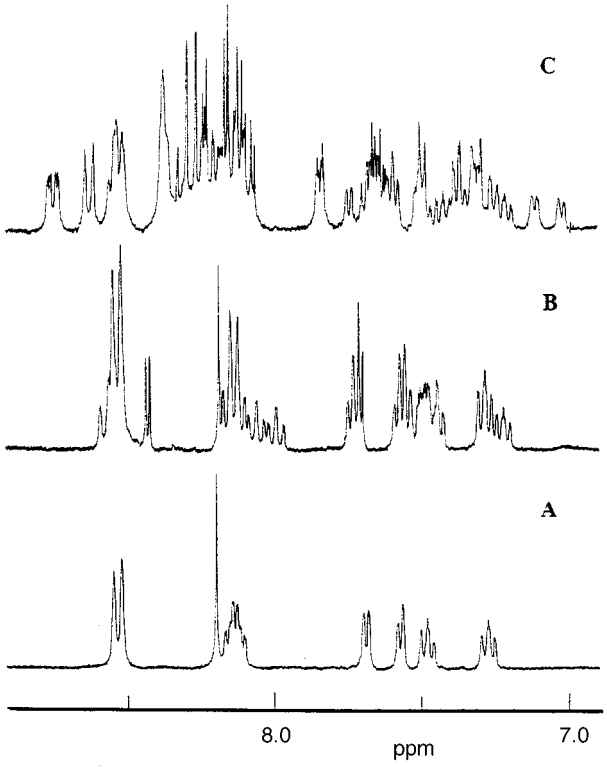


Fig. 11 ^{1}H NMR spectra (aromatic region; 300 MHz; $[^2H_6]$acetone solvent) of the D^3-diastereoisomeric forms of (A) $[\{Ru(bpy)_2\}_3\{\mu\text{- HAT}\}]^{6+}$, (B) $[\{Ru(bpy)_2\}_2\{Os(bpy)_2\}\{\mu\text{-HAT}\}]^{6+}$, and (C) $[\{Ru(bpy)_2\}\{Ru(Me_2\text{-}bpy)_2\}\{Ru(phen)_2\}\{\mu\text{-HAT}\}]^{6+}$.[15,29]

Undoubtedly, the availability of data from detailed investigations of this type, the accessibility of higher field NMR facilities and the development of improved high-resolution NMR techniques will allow the characterisation of stereoisomers of higher nucleate assemblies to become routine.

5 Chromatographic techniques

In our studies, the use of cation exchange chromatography (with SP Sephadex C-25 as the support) has been a significant factor in the isolation of individual stereoisomers (geometrical isomers, diastereoisomers and enantiomers) of mono- and polynuclear ruthenium complexes with bidentate α,α′-diimine ligands.

Using a wide range of organic and aliphatic counter-anions in the aqueous eluents, it is apparent that the rate of passage down the column for any cation is profoundly influenced by the anion present. Certain anions are particularly effective, including aromatic anions such as 4-toluate, toluene-4-sulfonate, *O,O′*-dibenzoyl-L-tartrate and di-4-toluoyl-L-tartrate, and longer chain aliphatic carboxylates such as hexanoate and octanoate.[30] The observation is consistent with a second-sphere association of the eluent anion with the cations, effectively reducing the overall charge of the cation and resulting in its increased elution rate.[10] Furthermore, in cases where there are stereoisomeric forms of the cations, differential associations with the anion may result in their separation:[30] geometrical isomers[31,32] and enantiomers[6,13,14] of mononuclear complexes, as well as diastereoisomers, enantiomers and geometrical isomers of di- and tri-nuclear species.[4,6,8,15,29]

A detailed ^{1}H NMR titration study has provided an interesting insight into the nature of these associations. As an example, the perturbations of the resonances of the cation host $[\{(Me_2bpy)_2Ru\}_2(\mu\text{-bpm})]^{4+}$ were measured as a function of the addition of sodium salts of various anions (guest) in D_2O solution.[30] In the majority of titration curves, a distinct change at 4 equivalents of the anion indicated a stoichiometry of 1 : 4, as would be expected on the basis of electrostatic attraction.

The perturbations (Δδ in ppm) observed for the bpm-H4/6, Me_2bpy-H3 and Me_2bpy-H6′ protons of the diastereoisomers of the dinuclear species after the addition of ten equivalents of the respective anions are shown in Fig. 12.[30]

The shifts observed for the two different diastereoisomers are similar, although smaller for the *rac* form. The most striking observation is that the aliphatic anions all induced downfield shifts in the protons of the dinuclear complex, while the shifts were upfield for the aromatic anions under the same conditions. The approach of a negative charge had been observed previously to cause downfield shifts in the ^{1}H NMR spectrum of a complex cation as a result of second sphere interactions,[34] in accordance with the present results for the aliphatic anions. The antithetic effect of the aromatic anions indicates that ring current (anisotropic) interactions of the anions on the protons of the associated complex, resulting in upfield shifts, are more significant. The presence of substituents at the *ortho*-position(s) to the carboxylate group in the aromatic anions 2-toluate and mesitoate led to great reductions in the shifts, implying that the aromatic interaction is being blocked and the H2/6 protons of the aromatic anion play an important role in the association, which suggests that the association relies on an edge-to-face π-stacking.[33] The effects showed little dependence on the basicity of the carboxylate, but as the chain length of the aliphatic anions increased greater shifts were observed: by implication there were larger associations as a consequence of the geometry and hydrophobicity of the anion relative to the complex cation.

There is some correlation between the magnitude of the shifts and the rate of passage down the column, which is not entirely unexpected as the former is undoubtedly influenced by the strength of the association. It is an interesting observation that in all the dinuclear cases studied, the *meso* diastereoisomer was eluted first. As discussed earlier in this review, the spatial relationship of the terminal ligands in ligand-bridged dinuclear

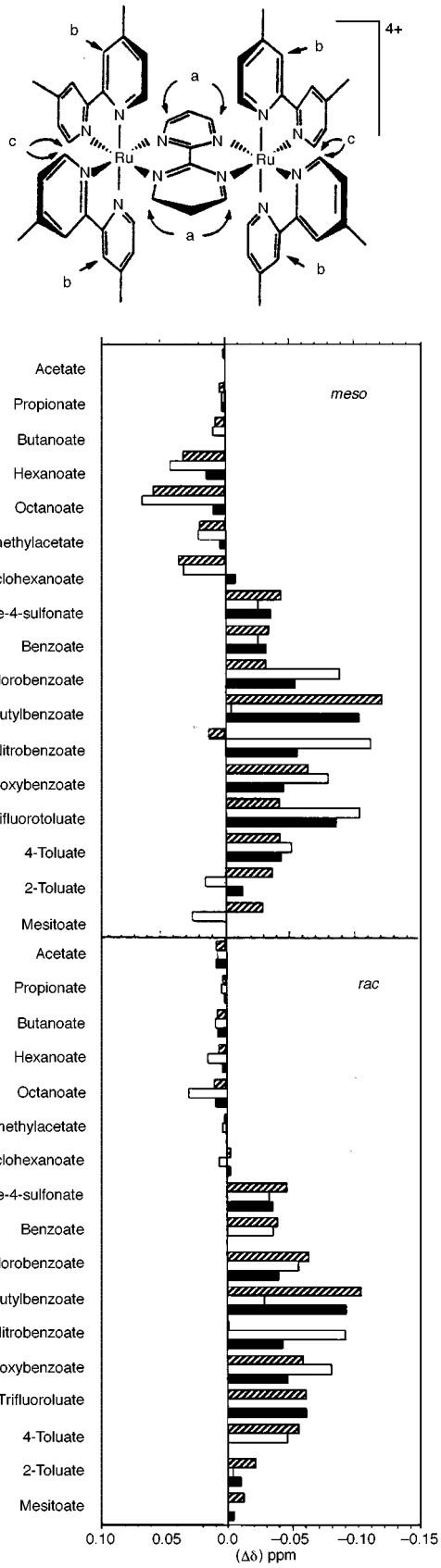


Fig. 12 The relative ^{1}H NMR signal (500 MHz) perturbations observed on the protons bpm-H4/6 (a; hatched), Me_2bpy-H3 (b; open) and Me_2bpy-H6′ (c; filled) respectively for *meso*- and *rac*-$[\{(Me_2bpy)_2Ru\}_2(\mu\text{-bpm})]Cl_4$ on the addition of 10 equiv. of the organic anions (D_2O solvent; 30 °C).[30]

complexes is dependent on the relative orientation of the 'bites' of the two bidentate ligating groups. However, a perusal of the $[\{Ru(bpy)_2\}_2(\mu\text{-bpm})]^{4+}$ (Fig. 2) and $[\{Ru(bpy)_2\}_2(\mu\text{-HAT})]^{4+}$ complexes (Fig. 3) reveals that the *meso* form in both cases has a cleft into which the associating anion may enter, despite the linear and angular relationship (respectively) of the ligating moieties of the bridging ligand in the two cases.

The determination of association constants of the various anions with the stereoisomers of the dinuclear species is rendered difficult by the 4 : 1 stoichiometric ratio of anion to cation. However, similar anion interactions may be expected with the simpler mononuclear species such as $[Ru(Me_2bpy)_3]^{2+}$, and to assess the magnitude of these associations, a series of titrations were carried out with this complex against the same series of anions. The titration curves obtained indicated a 2 : 1 stoichiometry and the magnitudes of the perturbations were similar to those observed for the dinuclear species.[30] The stability constants for the association of the first (k_{stab1}) anion with the mononuclear target were typically *ca.* 100 $dm^3\ mol^{-1}$ for the anions identified as showing a strong interaction with the cations.[30] While these values are small they are nevertheless significant, especially in aqueous solution where the polarity of the solvent effectively negates the electrostatic attractions.

While an intimate understanding of the nature of these associations allows a much more efficient application of the technique to the chromatogrpahic separation of stereoisomers of mononuclear and oligonuclear assemblies, the connotations extend beyond the chromatographic process. For example, the interaction of metal complexes with biological molecules (such as polynucleotides) is of considerable interest as metal centres have potential as sensitisers in sequencing and in site-specific cleavage processes.[35,36] The nature of such interactions is not always well understood, but there are undoubtedly aspects of π-stacking, hydrophobicity and the chirality of the metal complex which influence intercalative and specific groove binding. The chromatographic separation of stereoisomers of mono- and oligo-nuclear species therefore offers not only a significantly larger stereochemical array of complexes as targets for such investigations, but also a means of interpreting the fundamental nature of the interaction itself. These aspects are currently under study.

6 Consequences of stereoisomerism on physical properties of ligand-bridged oligomeric complexes

There are a number of consequences of the isolation of the stereoisomers of mono- and oligo-nuclear complexes of the above types, given their potential in the development of new materials for photochemical molecular devices.[2] In terms of identification, each diastereoisomeric or geometrical form of a complex will have its own distinctive NMR spectrum, so that the spectral characteristics of an isomeric mixture are of minimal use in structural elucidation, particularly for higher nucleate assemblies. For such mixtures, bulk characteristics such as nuclearity (from mass spectral measurements) or spectral properties (which will be averages of the stereoisomeric mixture) are accessible, but contain no intimate structural information. The isolation of the individual stereoisomers has allowed not only structural assignment, but also a general assessment of the factors contributing to the various physical characteristics.

More importantly, there are spatial consequences on physical properties in these assemblies:[7] the dependence of such fundamental features as intramolecular energy and electron transfer processes on the stereochemical relationship of components in a polymetallic supramolecular structure may well be an essential factor in the design of new materials. We have recently reported three examples where differences have been observed in the spectral, electrochemical and photophysical properties of stereoisomers in mononuclear[5,32] and dinuclear/trinuclear assemblies.[4,6,7]

The first of these examples involves mononuclear complexes, and although such species have not been the subject of this review, the results are salient to the present discussion. A comparative study of the photophysics[5] of the four separate geometric isomers (one *trans* and three *cis*[30]) of the chromophore-quencher triad $[Ru(Me_2bpy)(bpyCH_2PTZ)(bpyCH_2MV^{2+})]^{4+}$ {$bpyCH_2PTZ$ = 10-[(4′-methyl-2,2′-bipyridin-4-yl)methyl]phenothiazine and $bpyCH_2MV^{2+}$ = 1-[(4′-methyl-2,2′-bipyridin-4-yl)methyl]-1′-methyl-4,4′-bipyridinediium cation} has shown that following metal-to-ligand charge transfer (MLCT) excitation by laser flash photolysis, the redox charge-separated states $[Ru^{II}(Me_2bpy)(bpyCH_2PTZ^{\cdot+})(bpyCH_2MV^{\cdot+})]^{4+}$ are formed rapidly (< 5 ns). While the driving force for the back electron transfer process from -MV^+ to -PTZ^+ is the same in every case, the rates are different for the four isomers, and k_{ET} varies from 4.5×10^6 to $8.7 \times 10^6\ s^{-1}$ in acetonitrile solution at 25 °C.

The second example involves a series of dinuclear complexes $[\{Ru(pp)_2\}_2(\mu\text{-BL})]^{2+}$ incorporating an α-azodiimine (such as apy and mapy) as the bridge and bpy or Me_2bpy as the terminal ligands.[4] The *meso* and *rac* diastereoisomeric forms of such species (Fig. 4) have been separated: electronic spectral and electrochemical studies indicate there are differences in intermetal communication between the diastereoisomeric forms.

The third example involves the *meso* and *rac* diastereoisomers of the dinuclear complexes $[\{Ru(pp)_2\}_2(\mu\text{-HAT})]^{4+}$ (Fig. 3) and the homochiral (Δ^3/Λ^3) and heterochiral ($\Delta^2\Lambda/\Lambda^2\Delta$) diastereoisomers of the trinuclear complexes $[\{Ru(pp)_2\}_3(\mu\text{-HAT})]^{6+}$ (Fig. 8), where pp = bpy or phen.[8] Emission studies of all the dinuclear species at room temperature indicate the relative luminescence quantum yields and the emission lifetimes significantly decrease for the *meso* compared with the *rac* diastereoisomers. While no significant differences were detected at room temperature in the diastereoisomeric forms of the trinuclear compounds, in a glass at low temperature (80 K) the luminescence lifetimes of the heterochiral diastereoisomer were slightly shorter than those of the homochiral form.[8]

While there are a limited number of examples of such studies of physical characteristics as a function of the stereochemical identity at this stage, the factors controlling such differences are not yet understood and their elucidation constitutes a significant challenge in supramolecular chemistry in the immediate future. The development of techniques such as those described in this review to realise separate stereoisomers in a wide variety of assemblies provides the means of addressing this important problem.

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