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Cobalt(III) Werner Complexes with 1,2-Diphenylethylenediamine Ligands: Readily Available, Inexpensive, and Modular Chiral Hydrogen Bond Donor Catalysts for Enantioselective Organic Synthesis

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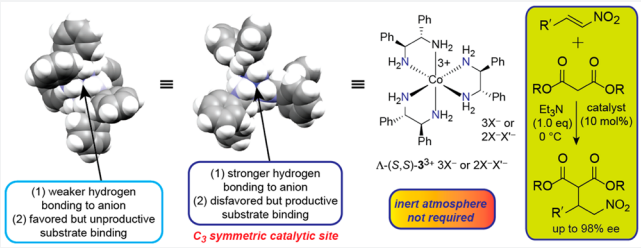
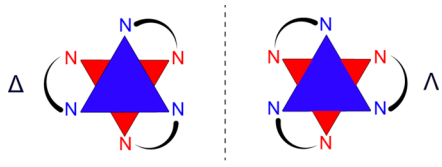
Supporting Information

ABSTRACT: In the quest for new catalysts that can deliver single enantiomer pharmaceuticals and agricultural chemicals, chemists have extensively mined the "chiral pool", with little in the way of inexpensive, readily available building blocks now remaining. It is found that Werner complexes based upon the D_3 symmetric chiral trication $[Co(en)_3]^{3+}$ (en = 1,2-ethylenediamine), which features an earth abundant metal and cheap ligand type, and was among the first inorganic compounds resolved into enantiomers 103 years ago, catalyze a valuable carbon−carbon bond forming reaction, the Michael addition of malonate esters to nitroalkenes, in high enantioselectivities and without requiring inert atmosphere conditions. The title catalysts, $[Co((S,S)\text{-dpen})_3]^{3+}$ $((S,S)\text{-}\mathbf{3}^{3+})$ $3X^-$, employ a commercially available chiral ligand, (*S*,*S*)-1,2-diphenylethylenediamine. The rates and ee values are functions of the configuration of the cobalt center (Λ/Δ) and the counteranions, which must be lipophilic to solubilize the trication in nonaqueous media. The highest enantioselectivities are obtained with Λ and $2Cl^-BAr_f^-$, $2BF_4^-BAr_f^-$, or $3BF_4^-$ salts ($BAr_f^- = B(3,5\text{-}C_6H_3(CF_3)_2)_4^-$). The substrates are not activated by metal coordination, but rather by second coordination sphere hydrogen bonding involving the ligating NH_2 groups. Crystal structures and NMR data indicate enthalpically stronger interactions with the NH moieties related by the C_3 symmetry axis, as opposed to those related by the C_2 symmetry axes; rate trends and other observations suggest this to be the catalytically active site. Both Λ- and Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ are effective catalysts for additions of β-ketoesters to $RO_2CN{=}NCO_2R$ species (99−86% yields, 81−76% ee), which provide carbon−nitrogen bonds and valuable precursors to α-amino acids.



The pervasive role of hydrogen bonding in enzymatic catalysis has been recognized for more than a half-century,[1] and recently numerous small molecule hydrogen bond donor catalysts have been developed,[2] in parallel with the growth of "organocatalysis".[3] Due to the desirability of single enantiomer pharmaceuticals and agrichemicals, enantiopure chiral donors have received particular focus.[2] However, from the standpoint of innovative new paradigms, much of the "chiral pool"[4] applicable to catalysis has been quite thoroughly picked over, especially with regard to inexpensive, readily available building blocks.

In this context, our attention was drawn to Werner complexes featuring the chiral tris(ethylenediamine) substituted trication $[Co(en)_3]^{3+}$, and related octahedral systems. These were the first inorganic compounds resolved into enantiomers some 103 years ago,[5] with the configurations of the helically chiral mirror images later denoted as Λ and Δ. Cobalt is an earth abundant metal, but none of these salts has ever been applied in any type of enantioselective organic reaction, despite facile resolution procedures. Given the mechanisms of most transition metal catalysts, many would presume the necessity of a metal based vacant coordination site to bind and activate a substrate. However, such d^6 cobalt(III) systems are "substitution inert",[6,7] especially at temperatures lower than 100 °C.



enantiomers of octahedral tris(1,2-diamine) metal complexes

We wondered about the possibility of an alternative binding/activation mode, in which the ligating NH_2 groups would function as hydrogen bond donors, leading to what could be termed "second coordination sphere promoted catalysis". Thus, nearly 80 crystal structures of salts of the formula $[Co(en)_3]^{3+}$ yX^{z-} (y/z = 3/1, 1.5/2, 1/3) were surveyed.[8] Every one showed significant NH···X hydrogen bonding, even when the anions were poor acceptors. Furthermore, data for related cobalt(III)

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complexes suggested pK_a values of 13−14,[9] or acidities greater than those of other hydrogen bond donors that are effective organocatalysts.[2]

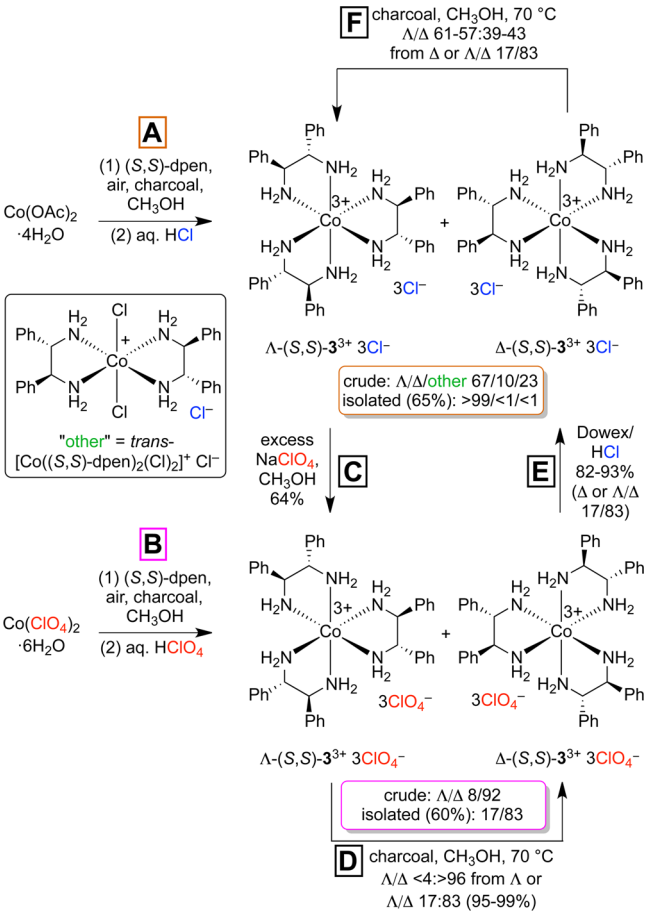
Cobalt(III) has an extensive aqueous chemistry, but water would be expected to compete with substrates for hydrogen bond donor sites, suppressing rates. Accordingly, we have shown that salts of the lipophilic BAr_f^- anion,[10] such as Δ-$[Co(en)_3]^{3+}$ $3BAr_f^-$ and *trans*-1,2-cyclohexanediamine analogues, are soluble in a variety of organic solvents.[11,12] However, enantioselectivities in screening reactions were disappointing. We now report that similar adducts of (*S*,*S*)-1,2-diphenylethylenediamine ((*S*,*S*)-dpen),[13,14] which is commercially available as either enantiomer,[15] afford high enantioselectivities in a benchmark carbon−carbon bond forming reaction, the addition of malonate esters to nitroalkenes,[16] as well as others. Together with recent studies involving metal catalysts with hydrogen bond donors *remote* from coordinating atoms,[17−20] this work firmly establishes the viability of highly enantioselective second coordination sphere promoted catalysis, and presages a "gold rush" on widely available NH-containing coordination compounds that have heretofore unrecognized potential as catalysts.

First, (*S*,*S*)-dpen was elaborated into a series of diastereomeric complexes Λ- and Δ-$[Co((S,S)\text{-dpen})_3]^{3+}$ $3X^-$ (Λ- and Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3X^-$), differing in the cobalt chirality, by adapting earlier procedures of Bosnich,[13] Mason,[14] and others (Supporting Information).[21] These feature substitution labile cobalt(II) educts, aerobic conditions to generate cobalt(III), and charcoal, which promotes the isomerization of cobalt(III) stereocenters.[22] As shown in Scheme 1 (step A), when the acetate complex $Co(OAc)_2{\cdot}4H_2O$ (or chloride $CoCl_2{\cdot}6H_2O$) was employed, workup with HCl gave a 67/10/23 mixture of the orange trichloride salt Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$,[13,14] the diastereomer Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$, and the green byproduct *trans*-$[Co((S,S)\text{-dpen})_2(Cl)_2]^+$ Cl^-.[23] These exhibited easily distinguished CHPh ^{13}C NMR signals (CD_3OD), and workup afforded diastereomerically pure Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$ (65%).

In contrast, syntheses conducted with the perchlorate complex $Co(ClO_4)_2{\cdot}6H_2O$ gave predominantly the opposite diastereomer of the tris(perchlorate) salt Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3ClO_4^-$ (Scheme 1, step B; 8:92 or 17:83 Λ/Δ, before or after workup). The minor diastereomer, Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3ClO_4^-$, could be isolated in 64% yield by a room temperature anion metathesis of the trichloride salt Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$ (step C). When Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3ClO_4^-$ was heated at 70 °C in CH_3OH in the presence of charcoal (150 h), equilibration to <4:>96 Λ/Δ mixtures gradually occurred, together with a minor amount of decomposition to an unidentified but easily separable species (16%). Under similar conditions, the 17:83 Λ/Δ mixture gave a <4:>96 Λ/Δ mixture in 99−95% yields (triplicate run). This salt or the 17:83 Λ/Δ mixture could be converted to the trichloride salt Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$ or a 17:83 Λ/Δ mixture in 82−93% yields by room temperature anion metathesis (step E). When these samples were heated at 70 °C in CH_3OH in the presence of charcoal (step F), equilibration to mixtures enriched in the opposite diastereomer Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$ occurred (61:39 to 57:43).

Steps D and F show that the trichloride and tris(perchlorate) salts of (*S*,*S*)-$\mathbf{3}^{3+}$ exhibit divergent Λ/Δ thermodynamic diastereoselectivities, paralleling the kinetic diastereoselectivities (steps A and B). Although the basis for this dichotomy remains under study, perchlorate is a very poor hydrogen bond acceptor, whereas chloride is a strong hydrogen bond

Scheme 1. Syntheses of Salts of the Formula $[Co((S,S)\text{-dpen})_3]^{3+}$ $3X^-$ ((*S*,*S*)-$\mathbf{3}^{3+}$ $3X^-$; X = Cl, ClO_4); Kinetic and Thermodynamic Λ/Δ Diastereoselectivities



acceptor.[24] Thus, we speculate that (1) Δ-(*S*,*S*)-$\mathbf{3}^{3+}$, favored with perchlorate, represents the trication that is more stable in the gas phase, and (2) Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ forms enthalpically stronger hydrogen bonds, and is thereby favored in condensed phases with good accepting counteranions. In any event, Scheme 1 provides two diastereomeric series of catalysts for study.

Next, lipophilic salts were prepared as exemplified for the Λ diastereomers in Scheme 2.[21] Anion metathesis gave the tris(BAr_f) salt Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3BAr_f^-$ in 94% yield (BAr_f^- = $B(3,5\text{-}C_6H_3(CF_3)_2)_4^-$). However, in optimizing this transformation, an "end point" was noted after adding one equivalent of $NaBAr_f$. Workup afforded a CH_2Cl_2 soluble mixed salt Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ with a surprising mobility on silica gel in 93% yield. The lower molecular weight and counteranion cost associated with this salt were viewed as advantageous. Metatheses with silver salts gave analogous mixed tetrafluoroborate and hexafluorophosphate salts, Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2BF_4^-BAr_f^-$ and Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2PF_6^-BAr_f^-$ (96−85%). Also, the tris(tetrafluoroborate) salt Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3BF_4^-$ was similarly prepared from Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3Cl^-$ (93%). This complex, which has less lipophilic counteranions, was insoluble in CH_2Cl_2, but readily dissolved in acetone and acetonitrile.

In all of the preceding compounds, the NH_2 protons are diastereotopic. Accordingly, they gave distinct ^1H NMR signals (br s), with those of Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ exhibiting a marked chemical shift difference, 4.31 ppm (δ 8.17, 3.86), as depicted in Figure s2 (Supporting Information). The NH_2 signals of Λ-

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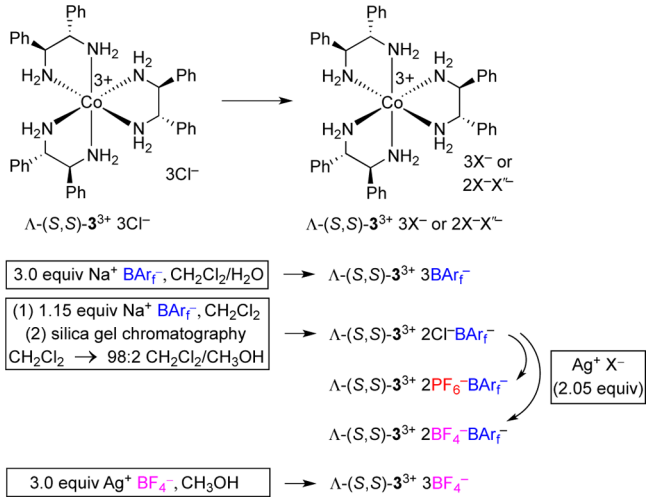
Scheme 2. Syntheses of Lipophilic Werner Salts (Yields: 83-96%)[a]



[a]The procedures for Δ disastereomers are analogous.

(*S*,*S*)-**3**$^{3+}$ 2BF$_4^-$BAr$_f^-$, Λ-(*S*,*S*)-**3**$^{3+}$ 2PF$_6^-$BAr$_f^-$, and Λ-(*S*,*S*)-**3**$^{3+}$ 3BAr$_f^-$, which feature progressively weaker hydrogen bond accepting anions, were only separated by 1.87, 1.67, and 0.86 ppm, respectively (δ 6.04/5.77/5.44 and 4.17/4.10/4.68). Thus, it was proposed that one set of NH$_2$ protons is much more disposed toward hydrogen bonding with the counter-anions than the other, with the magnitude of the downfield shift reflecting the strength of the interaction. The diastereomeric Δ trication was posited above to give enthalpically weaker hydrogen bonds. Accordingly, the chemical shift difference for Δ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$ was much less (1.28 vs 4.31 ppm). However, that for Δ-(*S*,*S*)-**3**$^{3+}$ 3BAr$_f^-$, which features a non-hydrogen bonding anion, was nearly equal to the Λ diastereomer (0.85 vs 0.86 ppm), suggesting intrinsic limiting differences associated with the trication core.

It has not yet been possible to obtain a crystal structure of one of the lipophilic salts. However, crystal structures of Λ- and Δ-(*S*,*S*)-**3**$^{3+}$ 3Cl$^-$ could be determined, as described in the Supporting Information. Views of the former are presented in Figure 1. As expected, the trication exhibits an idealized D$_3$ geometry, with a principal C$_3$ symmetry axis and three C$_2$ symmetry axes that define a plane perpendicular to the principal axis. The three NH protons on each of the two "C$_3$ faces" are oriented in a convergent manner that should afford particularly strong hydrogen bonds. The two protons on each of three "C$_2$ faces" are also effectively aligned for hydrogen bonding, but the enthaplic interactions should be lower, consistent with the more facile exchange of the first chloride ion by BAr$_f^-$ (Scheme 2). A similar motif is found with the opposite diastereomer Δ-(*S*,*S*)-**3**$^{3+}$ 3Cl$^-$, but the protons on the C$_3$ faces are oriented in a divergent manner, and the C$_2$ faces are much more congested, precluding simultaneous bonding of chloride to both NH protons (Figure s1, Supporting Information). In any event, for both diastereomers of the mixed salts (*S*,*S*)-**3**$^{3+}$ 2X$^-$BAr$_f^-$, the dominant hydrogen bonding interactions should involve X$^-$ and the C$_3$ faces.

The complexes in Scheme 2 were screened as catalysts for additions of malonate esters to *trans*-β-nitrostyrene (**4a**),[16] as summarized in Scheme 3. As shown in entries 1 and 2, di(isopropyl) malonate (**5a**) and **4a** were combined in the presence of Et$_3$N (1.0 equiv) and Λ- or Δ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$

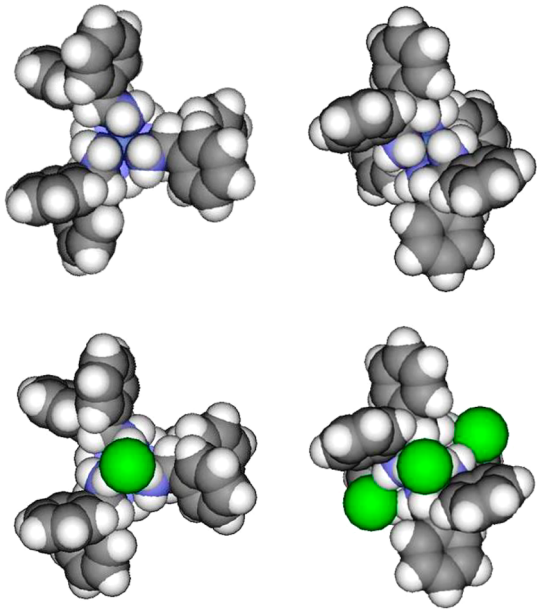
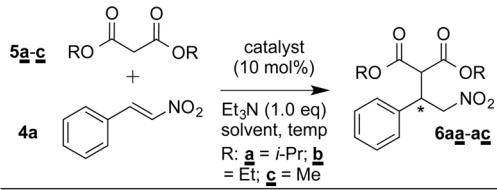


Figure 1. Thermal ellipsoid diagram (50% probability level) of Λ-(*S*,*S*)-**3**$^{3+}$ 3Cl$^-$·2H$_2$O·2CH$_3$OH with solvent molecules removed for clarity. Upper left and right, views down the idealized C$_3$ and C$_2$ axes with chloride ions omitted; lower left and right, analogous views with chloride ions.

Scheme 3. Initial Screening Reactions: Data for Additions of Dialkyl Malonates (5) to *trans*-β-Nitrostyrene (4a) Catalyzed by Λ- and Δ-(*S*,*S*)-3^{3+} 2Cl$^-$BAr$_f^-$ in CD$_2$Cl$_2$ at Room Temperature (Entries 1−6), and Additions Catalyzed by Other Salts of Λ-(*S*,*S*)-3^{3+} in Acetone-*d*$_6$ at 0 °C (Entries 7−11)



entry	malonate ester	catalyst	conversion (%) (time)[a]	ee (%) (config)[b]
A. CD$_2$Cl$_2$, rt[c]				
1	**5a**	Λ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	88 (2 h)	80 (*R*)
2	**5a**	Δ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	>99 (2 h)	76 (*S*)
3	**5b**	Λ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	94 (3 h)	79 (*R*)
4	**5b**	Δ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	99 (1 h)	59 (*S*)
5	**5c**	Λ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	>99 (2 h)	82 (*R*)
6	**5c**	Δ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	>99 (1 h)	40 (*S*)
B. acetone-*d*$_6$, 0 °C[c]				
7	**5c**	Λ-(*S*,*S*)-**3**$^{3+}$ 2Cl$^-$BAr$_f^-$	93 (24 h)	87 (*R*)
8	**5c**	Λ-(*S*,*S*)-**3**$^{3+}$ 2BF$_4^-$BAr$_f^-$	94 (10 h)	90 (*R*)
9	**5c**	Λ-(*S*,*S*)-**3**$^{3+}$ 2PF$_6^-$BAr$_f^-$	>99 (4 h)	85 (*R*)
10	**5c**	Λ-(*S*,*S*)-**3**$^{3+}$ 3BAr$_f^-$	>99 (1 h)	80 (*R*)
11	**5c**	Λ-(*S*,*S*)-**3**$^{3+}$ 3BF$_4^-$	>99 (6 h)	93 (*R*)

[a]The conversion was determined by ^{1}H NMR integration of the *p*-C$_6$H$_5$ signal of **4a** versus the internal standard Ph$_2$SiMe$_2$. [b]Enantioselectivities were determined by chiral HPLC analyses. [c]Reactions were conducted under ambient air atmospheres.

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(10 mol %) under an ambient air atmosphere in CD_2Cl_2 at room temperature. Conversions were monitored by ^{1}H NMR in the presence of an internal standard. Over the course of 2 h, the enantiomeric addition products (*R*)- or (*S*)-**6aa** formed in 88 and >99% yields and 80% ee and 76% ee, respectively, as assayed by chiral HPLC. These impressive lead results also established that the cobalt configurations control the product configuration. However, when diethyl and dimethyl malonate (**5b**,**c**) were investigated, it became clear that Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ was a more enantioselective catalyst (**6ab**, 79% (*R*) or 59% (*S*) ee; **6ac**, 82% (*R*) or 40% (*S*) ee). In optimization experiments, acetone was found to be a somewhat better solvent, especially at lower temperatures, and CH_3CN gave in many cases comparable data. Other bases were examined, but none gave better results than Et_3N.

Other salts were investigated, now at 0 °C in acetone-d_6 with **5c**, as summarized in entries 7−11 of Scheme 3. With Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$, the ee value of the resulting **6ac** increased to 87%. The other mixed salts Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2BF_4^-BAr_f^-$ and Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2PF_6^-BAr_f^-$ were comparably effective (90%, 85% ee). The slightly higher enantioselectivity with the former was reproducible, prompting Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3BF_4^-$ to be synthesized (above) and tested. Interestingly, this catalyst gave the highest ee value of all (93%). In contrast, the tris(BAr_f) salt Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3BAr_f^-$ was the least enantioselective catalyst, with an ee value of 80%.

The catalysts exhibited significant reactivity differences, as signaled by the reaction times in Scheme 3. Hence, rate profiles were measured in CD_2Cl_2, but using a lower catalyst loading (2 mol %), a less reactive Michael acceptor (*trans*-4-methoxy-*β*-nitrostyrene, **4d**), and a lower Et_3N charge (0.35 equiv) to enhance differentiation. As shown in Figure 2, the less enantioselective diastereomer, Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ (red ■), was significantly more active catalyst than the more enantioselective diastereomer Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ (blue ◆). Among the Λ diastereomers, rates increased as the chloride anions in Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ were replaced by progressively more weakly hydrogen bonding anions ($2Cl^- < 2BF_4^- < 2PF_6^- < 2BAr_f^-$).

We interpret these data as indicative of substrate activation at the more strongly hydrogen bonding C_3 trication sites, subsequent to initial anion dissociation. In the mixed salts,

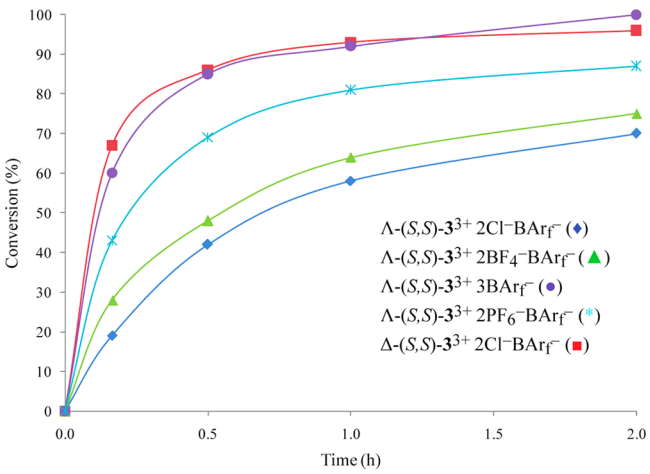

Figure 2. Rate profiles for additions of dimethyl malonate (**5c**) to *trans*-4-methoxy-*β*-nitrostyrene (**4d**) catalyzed by lipophilic Werner salts. Conditions: 2 mol % catalyst, 0.35 equiv of Et_3N, CD_2Cl_2, rt.

the C_2 sites should be unencumbered, or very weakly interacting with BAr_f^-; if these were responsible for catalysis, comparable rates would be expected as the other anions are varied.[25] Faster catalysis with the diastereomer Δ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ logically follows from the enthalpically weaker interactions of the Δ trication with chloride ion. The lower enantioselectivities would then be ascribed to less favorable architectural factors. With Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2X^-BAr_f^-$, the moderate dependence of enantioselectivities upon the anion X^- might reflect the continued association of X^- with one of the two C_3 sites.

Despite any oversimplifications in the preceding models, the enantioselectivity trends in Scheme 3 generally hold for a variety of nitroalkene substrates, as summarized in Scheme 4. Reactions were conducted in acetone at 0 °C, with the rates and yields determined by ^{1}H NMR (Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$) or isolation following chromatography (Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2BF_4^-BAr_f^-$, Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $3BF_4^-$). In eight out of ten cases, the second catalyst afforded higher enantioselectivities than the first; the third tris(tetrafluoroborate) catalyst was superior in all cases, delivering an average of 94% ee for the aryl-substituted nitroalkenes. A good ee value was also obtained with an alkyl-substituted nitroalkene (**4l**, 86%).[26] Although our enantioselectivities have been matched or slightly exceeded by organic hydrogen bond donor catalysts,[16,26] these were in all cases bifunctional, incorporating the amine base. Thus, Scheme 4 represents an impressive debut for a new catalyst family at an early stage of development. Furthermore, Λ-(*S*,*S*)-$\mathbf{3}^{3+}$ $2Cl^-BAr_f^-$ is easily recovered in near quantitative yields chromatographically (Supporting Information).

In order to demonstrate broad synthetic applicability for these catalysts, other transformations known to be accelerated by hydrogen bond donors were briefly investigated. In scout experiments, enantioselectivities of >50% ee have been found for analogous additions of the phosphorus hydrogen bond of $(PhO)_2P(=O)H$ to **4a**.[27] However, reactions involving entirely different educts, the azodicarboxylate diester **7** and cyclic *β*-ketoesters **8a**,**b**, are highlighted in Scheme 5. At 5 mol % catalyst loadings in the presence of *N*-methylmorpholine (1.0 equiv), electrophilic amination smoothly occurred to give the hydrazines **9a**,**b** in 86−99% isolated yields and 76−81% ee (unoptimized).[28] Both diastereomers of the trication (*S*,*S*)-$\mathbf{3}^{3+}$ are now comparably effective, and even higher ee values have been obtained with salts of anions different from those described above. Adducts of the type **9a**,**b** are easily elaborated to a variety of *α*-amino acid derivatives.[29]

Additional topics merit emphasis. First, analogues of dpen with substituted aryl groups are readily available,[30] and chiral counteranions are easily introduced by extending Scheme 2. Thus, it should be possible to optimize catalysis by exploiting these diversity elements, and by synthesizing bifunctional tertiary amine containing analogues.[31] Second, many chiral ligands with a C_3 symmetry axis are known, but metal containing catalysts in which the active sites have C_3 symmetry (i.e., devoid of symmetry lowering ancillary ligands) are much less common, especially with transition metals.[32] We presently favor transition state assemblies in which *both* substrates interact (although perhaps not exclusively) with a C_3 site. Third, note that most other hydrogen bond donor catalysts feature two donor groups (e.g., thioureas). Since, per the crystallographic data[8] and other evidence, the title complexes are capable of 3−5 or more simultaneous NH interactions, they can potentially give rise to new chemistries, i.e., transformations

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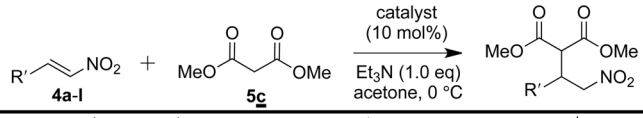
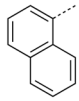
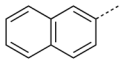
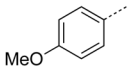
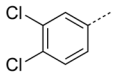
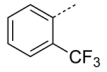
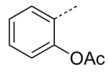
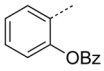
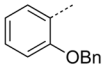
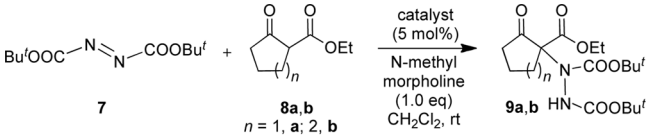
Scheme 4. Substrate Scope. Data for additions of Dimethyl Malonates (5c) to Nitroalkenes Catalyzed by Λ-(*S*,*S*)-3^{3+} $2Cl^-BAr_f^-$, Λ-(*S*,*S*)-3^{3+} $2BF_4^-$ BAr_f^-, and Λ-(*S*,*S*)-3^{3+} $3BF_4^-$



R′	alkene/ product	Λ-(*S*,*S*)-3^{3+} $2Cl^-BAr_f^-$ time (h)[a]	yield (%)[b]	ee (%)[c]	Λ-(*S*,*S*)-3^{3+} $2BF_4^-BAr_f^-$ time (h)[a]	yield (%)[d]	ee (%)[c]	Λ-(*S*,*S*)-3^{3+} $3BF_4^-$ time (h)[a]	yield (%)[d]	ee (%)[c]
	4a/6ac	15	94	87 *R*	12	97	90 *R*	6	97	93 *R*
	**4b/6bc**	20	>99	92 *R*	12	98	93 *R*	12	98	95 *R*
	**4c/6cc**	20	95	88 *R*	12	92	83 *R*	12	96	93 *R*
	**4d/6dc**	20	95	82 *R*	18	87	78 *R*	12	95	85 *R*
	**4e/6ec**	20	>99	80 *R*	12	94	90 *R*	12	93	93 *R*
	4f/6fc	24	98	81 *R*	12	86	86 *R*	-	-	-
	**4g/6gc**	20	>99	90 *R*	12	98	93 *R*	12	97	95 *R*
	**4h/6hc**	21	98	84 *R*	12	96	94 *R*	12	97	96 *R*
	**4i/6ic**	48	94	92 *R*	18	86	93 *R*	12	95	96 *R*
	**4j/6jc**	22	98	94 *R*	12	95	96 *R*	12	98	98 *R*
	4k/6kc	-	-	-	12	91	91 *S*	12	96	92 *S*
	4l/6lc	-	-	-	12	83	80 *S*	18	93	86 *S*

[a]Reactions were conducted under ambient air atmospheres. [b]Yields were determined by ^{1}H NMR integration of a nitroolefin and/or product signal versus the internal standard Ph_2SiMe_2. [c]Enantioselectivities were determined by chiral HPLC analyses. [d]Isolated yield after column chromatography.

Scheme 5. Enantioselective Amination of *β*-Ketoesters



	catalyst	yield	ee
9a (time = 1.5 h)	Λ-(*S*,*S*)-3^{3+} $2Cl^-$ BAr_f^-	98%	77% (*S*)
	Δ-(*S*,*S*)-3^{3+} $2Cl^-$ BAr_f^-	99%	76% (*R*)
9b (time = 12 h)	Λ-(*S*,*S*)-3^{3+} $2Cl^-$ BAr_f^-	86%	79% (*S*)
	Δ-(*S*,*S*)-3^{3+} $2Cl^-$ BAr_f^-	88%	81% (*R*)

that cannot be realized with established catalysts. Efforts involving all of these themes are in progress and will be reported in due course. Finally, together with other recent work involving metal catalysts with hydrogen bond donors *remote* from coordinating atoms,[17−20] this study underscores the rich possibilities associated with enantioselective second coordination sphere promoted catalysis. This may presage a revival of interest in classical NH coordination compounds, many of which feature inexpensive metals and ligands, can be utilized under an air atmosphere as in the above reactions, and can (when chiral) easily be obtained in enantiopure form. Such systems promise, in both conceptual and practical senses, to be transformational new additions to the chiral pool.

■ ASSOCIATED CONTENT

Supporting Information

Data involving starting materials, instrumentation, catalyst synthesis, catalytic reactions, product characterization including chiral HPLC traces, and X-ray crystallography including CIF files; selected NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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†The first two authors contributed equally to the experimental work.

Notes

The authors declare no competing financial interest.

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