Expanding the Family of Octahedral Chiral-at-Metal Cobalt(III) Catalysts by Introducing Tertiary Amine Moiety into the Ligand

Tat'yana F. Savel'yeva 1, Olga V. Khromova 1, Vladimir A. Larionov 1,2,* and Alexander F. Smol'yakov 1, Ivan V. Fedyanin 1, Yuri N. Belokon 1,* and Victor I. Maleev 1

1) A.N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences (INEOS RAS), Vavilov Str. 28, 119991 Moscow, Russia; saveleva40@list.ru (T.F.S.); olvichrom@gmail.com (O.V.K.); rengenhi@gmail.com (A.F.S.); octy@xlab.ineos.ac.ru (I.V.F.); vint@ineos.ac.ru (V.I.M.)
2) Department of Chemistry, Peoples’ Friendship University of Russia (RUDN University), Mikhukho-Maklaya Str. 6, 117198 Moscow, Russia

* Correspondence: larionov@ineos.ac.ru (V.A.L.); yubel@ineos.ac.ru (Y.N.B.); Tel.: +7-499-135-5047 (V.A.L.)

Abstract: Chiral metal-templated complexes are attractive catalysts for organic synthetic transformations. Herein, we introduce a novel chiral cobalt(III)-templated complex based on chiral trans-3,4-diamino-1-benzylpyrrolidine and 3,5-di-tert-butyl-salicylaldehyde which features both hydrogen bond donor and Brønsted base functionalities. The obtained complexes were fully characterized by 1H, 13C NMR, IR-, UV-vis, CD-spectroscopy and by a single X-ray diffraction analysis. It was shown that chlorine anion is connected with amino groups of the complex via a hydrogen bonding, DFT calculations of charges and molecular electrostatic potential of the cobalt(III) complex showed that the basicity of the complex is certainly diminished as compared with the routine tertiary amines but the acidity of the conjugated acid of the complex should be increased. Thus, the catalytic potential of the complex may be much greater as a chiral acid than a chiral base. We believe that this work opens a new way in chiral bifunctional catalyst design.

Keywords: metal-templated complex; chirality; chiral-at-metal; cobalt(III); hydrogen bond donor; Schiff base; Brønsted base

1. Introduction

Chiral stereochemically inert, coordinatively saturated metal complexes of Co, Cr, Rh, Ir or Ru presented a perspective class of “organic catalysts in disguise” which were applied in various asymmetric organic reactions [1–4]. In these complexes, the metal center can play several important roles: (1) to activate the coordinated ligands converting them into efficient hydrogen bond donors/acceptors [5–34]; (2) to serve as a chiral center (metal-centered chirality) providing a well-defined chiral environment [35–51] (in case of octahedral geometry of the complexes due to the mutual meridional arrangement of the chiral or achiral ligands around the metal ion with ∆- (left-handed propeller) or Δ-configurations (right-handed propeller)) [1–11,13–32,35–51]; (3) in addition, some of the complexes can serve as photosensitizers [47,48]. These features impart superior advantages to such complexes over the classical organocatalysts.

The pioneering work of Gladysz et al. was the first example of such catalysis based on chiral Werner salts [4], although with a moderate asymmetric efficiency [5]. Later, a novel generation of such catalysts proved to be much more efficient [17]. Particularly striking was the efficiency of a chiral iridium complex developed by the Meggers group in asymmetric conjugate reduction of nitroalkenes with high enantioselectivity at parts-per-million loadings [19].

Earlier, we prepared diastereoisomerically pure cobalt(III) complexes from the Schiff bases of substituted salicylaldehydes with chiral 1,2-diamines and Co(III) salts [6,8,10]. The complexes (Figure 1a) possess both chirality at the ligand and metal-center [3,8,10,13].
The formation of the complexes occurred stereospecifically with only one diastereoisomer, \( \Lambda(R,R) \)-1 or \( \Delta(S,S) \)-1, formed from the corresponding diamines. The NH\(_2\) groups of the ligands were coordinated to the metal ion and their acidities and their hydrogen bonding donor (HBD) abilities were greatly boosted by the coordination. Expectedly, complexes 1 (Figure 1a) proved to be efficient and recyclable hydrogen bond donor (HBD) catalysts for several important asymmetric transformations [6,8,10,13,18,26,28]. The transformation included trimethylsilylcyanation of benzaldehyde [6] and asymmetric alkyl halide alkylation of glycine derivatives [8,28], leading to a general protocol for enantiomerically enriched amino acid synthesis. In addition, Michael addition to the same glycine derivative [10] allowed the preparation of a series of enantiomerically enriched glutamic acid derivatives. For example, the activation of O’Donnell’s substrate and enantiocontrol by the complex 1 via multiple hydrogen bonding interactions is depicted in Figure 1c [10].

The epoxidation of chalcones under phase-transfer conditions [13], as well as the synthesis of cyclic carbonates from epoxides and carbon dioxide [13,18] were other examples of the performance of the catalytic family. The catalysts were even able to promote the redox reaction of naphthol couplings [26].

2. Results and Discussion

2.1. Synthesis of the Complexes

The chiral cobalt(III)-templated complex 2 was prepared similarly to the earlier described [8] general procedure (Scheme 1). Accordingly, \( \Lambda(R,R) \)-2 was obtained in a 13% yield. The complex was isolated by a flash chromatography on SiO\(_2\) (Scheme 1). Simi-
larly, a complex \( \Delta(S,S)-2 \) was prepared starting from \((S,S)-3,4\)-diaminopyrrolidine. Notably, both diastereoisomers of 2 were prepared stereoselectively without any amount of the alternative isomers formed in the reaction.

Scheme 1. The synthesis of the cobalt(III) complex \( \Lambda(R,R)-2 \).

2.2. Characterization of the Complexes 2

Complexes \( \Lambda(R,R)-2 \) and \( \Delta(S,S)-2 \) were characterized by \(^1H\), \(^{13}C\) NMR, IR-, UV-vis, CD-spectroscopy and elemental analysis. Besides, the structures of 2 were unambiguously determined by the single crystal X-ray diffraction analysis (Figure 2). Unfortunately, we failed to obtain suitable single crystals of both diastereoisomerically pure \( \Lambda(R,R)-2 \) and \( \Delta(S,S)-2 \). Still, a 1/1 mixture of the diastereoisomers could be crystallized from a solvent system—MeCN/hexanes. The mixture of 2 crystallized into \( P\bar{1} \) space group and the crystal data was collected at 120 K. Since one tert-butyl group (attached to a salicylaldehyde) was disordered over two positions, the refined occupancies were 0.54/0.46. Two tridentate NNO ligands are coordinated to cobalt ion forming a regular octahedral geometry. The \( \Lambda \)- or \( \Delta \)-configurations were attributed according to left or right helical mutual orientations of their tridentate ligands relative to the \( C_2 \) symmetry axis [49–51]. The three positive charges of cobalt(III) central ion were compensated by the two ionized phenolic oxygen atoms and the halide atom. Atoms O1 and N2 lie in axial position due to their longer distances (3.882 Å) in comparison with O2···N5 (3.875 Å) and N1···N4 (3.807 Å). NH groups are hydrogen bonded to the chlorine anion as indicated by the distances of N2–H···Cl1 and N5–H···Cl1 equal to 2.336 Å and 2.384 Å correspondingly, which is shorter than the same type of bonds in the analogous complexes derived from 1,2-diaminocyclohexane (2.448 Å) [6,8,52]. Besides, the chlorine anion coordinated to the third NH group of the second molecule of the complex in the unit cell, and this bond is a little bit longer (2.446 Å). The hydrogen bonding between the amino group and the chlorine anion was also found in \( \text{CH}_2\text{Cl}_2 \) solution which was testified by the IR spectra where the N–H···Cl stretching vibrations were observed in the region of 3200–3100 cm\(^{-1}\) (see Figure S3 in the Supplementary Materials).

The CD spectra of \( \Lambda(R,R)-2 \) and \( \Delta(S,S)-2 \) are shown in Figure 3, and confirm their mirror-image structures. The complex \( \Lambda(R,R)-2 \) has an optical rotation \([\alpha]_D^{25} -2292 \) (c 0.02, MeOH), whereas \( \Delta(S,S)-2 \)—\([\alpha]_D^{25} +2103 \) (c 0.04, MeOH). The UV-vis spectrum of the cobalt complex \( \Lambda(R,R)-2 \) was recorded in \( \text{CH}_2\text{Cl}_2 \) (see Figure S4 in the Supplementary Materials). The spectrum showed an intense band at 408 nm, which could be associated with the ligand-to-metal charge transfer transition, and confirmed the coordination of the imine and amine nitrogen atoms to the central Co(III) atom. A less intense band at 500 and 700 nm could be assigned to \( d \rightarrow d \) transitions (see Figure S4 in the Supplementary Materials).
2.3. Catalytic Activity of the Complex 2

The catalytic properties of the Co(III) complexes 2 could be expected to come from the hydrogen bonding of the NH groups and the tertiary amino group of the ligand skeletons. The group in its turn could be basic enough to affect the ionization of some CH acids or function as acidic site in case of the group protonation.

We evaluated the catalytic performance of the complex 2 in benchmark asymmetric reactions [13] (Scheme 2, for details see Supplementary Materials). Although the complex...
2 could catalyze the epoxidation of chalcone (Scheme 2a) and kinetic resolution of racemic chalcone epoxide with CO\(_2\) (Scheme 2b), its activity was poor in terms of both enantioselectivity of the products and the conversion of the starting material as compared with the performance of 1 [13]. Next, we tested 2 in Michael addition reaction of ethyl malonate to trans-\(\beta\)-nitrostyrene. Unfortunately, the preliminary results showed that the Brønsted basicity of the complex 2 was not enough to catalyze this reaction, even under heating (see Supplementary Materials).

(a) Epoxidation of chalcone

![Epoxidation of chalcone](image)

\[ \text{cat. } \Delta(S,S)-2 \text{: conv. } 15\%, 25\% \text{ ee} \]

\[ \text{cat. } \Delta(S,S)-1 \text{: conv. } 84\%, 55\% \text{ ee (ref. 13)} \]

(b) Kinetic resolution of chalcone epoxide with CO\(_2\)

![Kinetic resolution of chalcone epoxide with CO\(_2\)](image)

\[ \text{cat. } \Delta(S,S)-1 \text{ I\textsuperscript{-}} \text{ conv. } 72\%, s=2.3 \text{ (ref. 13)} \]

Scheme 2. Asymmetric reactions catalyzed by the cobalt(III) complex \(\Delta(S,S)-2\): (a) Epoxidation of chalcone; (b) Kinetic resolution of chalcone epoxide with CO\(_2\).

2.4. DFT Calculations of Charges and Molecular Electrostatic Potential of the Complex 2

In order to access the possible basicity of the tertiary amino groups of the ligands, we performed the DFT calculations of the parameters. For this purpose, we have optimized the cation using PBE0/def2-TZVP level of theory and calculated charges and molecular electrostatic potential (MEP) on its surface.

Whereas the NPA charges [53] that are often used to describe reactivity are closely similar for the tertiary amine nitrogen atoms N3 and N6 in 2 (−0.40 e) and in the triethylamine molecule (−0.42 e), the CHELPG charges [54] that are fitted to molecular electrostatic potential (−0.31 and −0.26 for N3 and N6) are significantly smaller by magnitude than in the case of triethylamine (−0.66). The distribution of the MEP on the molecular surface (Figure 4) shows that the regions close to the N atoms are either characterized by significantly positive electrostatic potential that prevents the protonation of the side chain amino groups or are strictly inaccessible. Thus, the basicity of the complex is certainly diminished as compared with the routine tertiary amines but the acidity of the conjugated acid of the complex should be increased. Thus, the catalytic potential of the complex 2 may be much greater as a chiral acid than a chiral base.
3. Materials and Methods

Proton nuclear magnetic resonance ($^1$H NMR) spectra and carbon nuclear magnetic resonance ($^{13}$C NMR) spectra were recorded on a Bruker Avance III-400 NMR spectrometer (BRUKER DALTONIK GmbH, Bremen, Germany) (operating at 400/101 MHz respectively, referring to $^1$H/$^{13}$C nucleus). Chemical shifts are reported in ppm relative to the residual solvent peak (CDCl$_3$: $\delta$ = 7.26 ppm for $^1$H NMR, $\delta$ = 77.2 for $^{13}$C NMR). NMR data are reported as follows: chemical shift, multiplicity, coupling constant, integration, and nucleus. X-ray diffraction data were collected on a Bruker SMART APEX CCD diffractometer (BRUKER DALTONIK GmbH, Bremen, Germany) ($\lambda$(MoK$_\alpha$) = 0.71072 Å, $\omega$-scans, 2$\theta$ < 58$^\circ$). Optical rotations were measured on a Perkin-Elmer 341 polarimeter (Perkin-Elmer, Waltham, MA, USA) in a 10 cm cell. UV-vis spectrum was measured in CH$_2$Cl$_2$ on Cary50 spectrometer (Varian Medical Systems, Palo Alto, MO, USA) using CaF$_2$ cells. IR spectrum of the compound was measured in CH$_2$Cl$_2$ on a Shimadzu IR Prestige 21 FT-IR equipped with MCT detector (Shimadzu, Kyoto, Japan) in CaF$_2$ cells. Circular dichroism (CD) curves were recorded on a Universal SKD-2MUF (Institute of Spectroscopy RAS, Troitsk, Russia). Elemental analyses were carried out in the Laboratory of Microanalysis of the A.N. Nesmeyanov Institute of Organoelement Compounds of the Russian Academy of Sciences (INEOS RAS).

All solvents purchased from commercial suppliers (Sigma-Aldrich, St. Louis, MO, USA) were used without further purification (CH$_2$Cl$_2$, CHCl$_3$, CDC$_3$, EtOH, MeOH, acetone). If not stated otherwise, flash column chromatography was performed with silica gel 60 M from Macherey-Nagel (Düren, Germany).
(R,R)- and (S,S)-3,4-diamino-1-benzylpyrrolidine were synthesized according to a literature procedure starting from commercially available D- or L-tartaric acids, respectively [55].

3.1. Synthesis of the Complexes 2

(R,R)- and (S,S)-3,4-diamino-1-benzylpyrrolidine (486 mg, 2.5 mmol, 1 equiv.) and NH4Cl (133 mg, 2.5 mmol, 1 equiv.) were dissolved in dry MeOH (20 mL) by stirring during 5 min, and the solvent was removed on a rotary evaporator. The resulting salt was dissolved in EtOH (30 mL) and 3,5-di-tert-butyalsalicylaldehyde (525 mg, 2.5 mmol) was added to the residue, and after 5 min stirring, the reaction solution became a deep yellow. Then, Na3[Co(CO3)3]·3H2O (460 g, 1.3 mmol, 0.6 equiv.) was added to this solution. The resulting dark-brown reaction mixture was heated at reflux for 4 h after which time the mixture was allowed to cool to room temperature. After removal of the solvent on a rotary evaporator, the resulting precipitate was dissolved in CH2Cl2 (20 mL), and the aqueous solution of sodium chloride (5 g in 20 mL) was added. After 1 h stirring, the organic layer was separated, and the aqueous layer was washed with CH2Cl2 (3 × 15 mL). The combined organic layers were dried over Na2SO4, the solvent was evaporated on a rotary evaporator, and the resulting residue was purified by silica column chromatography (eluent: CHCl3/acetone 5:1 → CHCl3/acetone 1:1 → MeOH) to separate from impurities, and further purified on LH-20 (eluent: benzene/EtOH 3:1) and, then, the complexes Λ(R,R)-2 or Δ(S,S)-2 were isolated as brown powders (150 mg, 0.17 mmol, 13% yield).

3.2. X-ray Diffraction Study

Single crystal X-ray study of the complex 2 was carried out in Center for Molecule Composition Studies of INEOS RAS. Dark-brown single crystals of the cobalt(III) complexes 2 were obtained by slow evaporation from acetonitrile/hexane mixture. The structures were solved by direct method and refined in anisotropic approximation for non-hydrogen atoms. Hydrogen atoms of methyl, methylene and aromatic fragments were calculated according to those idealized geometry and refined with constraints applied to C–H and N–H bond lengths and equivalent displacement parameters \( U_{eq}(H) = 1.2U_{eq}(X) \), \( X \)—central atom of \( XH_2 \) group; \( U_{eq}(H) = 1.5U_{eq}(Y) \), \( Y \)—central atom of \( YH_3 \) group. Analysis of residual electron density and displacement parameters in 2 has shown that tert-butyl group is disordered. All structures were solved with the ShelXT program [56] and refined with the ShelXL program [57]. Molecular graphics was drawn using OLEX2 program [58]. Experimental details and crystal parameters are listed in Table S1 (see Supplementary Materials). CCDC 2050585 contains the supplementary crystallographic data for complex 2. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

3.3. DFT Calculations

Geometry optimization of the cation was performed with ORCA [59] software package using the density functional theory. The combination of PBE0-D3 [60,61] functional and def2-TZVP [62] basis set was used. NPA charges were calculated with Janpa [63] program; the calculation of CHELPG charges and MEP was performed using Multiwfn program [64]. The molecular surface for MEP calculation was defined by an electron density isosurface with a value of 0.001 au.

4. Conclusions

In conclusion, here we reported a novel chiral cobalt(III)-templated complex featuring tertiary amine moiety (Brønsted base functionality) which expands the family of octahedral chiral-at-metal cobalt(III) complexes for applications in asymmetric catalysis. Compared to the previously reported chiral cobalt(III) hydrogen bond donor catalysts, the tertiary amino groups in the ligand sphere of the complex can be basic enough (Brønsted base center) to affect the ionization of some CH acids or function as an acidic site in case of the group protonation making the complex 2 a bifunctional asymmetric catalyst. The DFT calculations of the parameter showed that the basicity of the complex is certainly diminished as
compared with the routine tertiary amines but the acidity of the conjugated acid of the complex should be increased. Thus, the catalytic potential of the complex 2 may be much greater as a chiral acid than a chiral base. We believe this work will open a new chapter in the field of chiral catalyst design. The application of the new chiral cobalt(III)-templated complex in challenging asymmetric transformations are underway in our laboratory.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/2073-4344/11/2/152/s1, Analytical data; Figure S1: $^1$H NMR spectrum of the complex 2; Figure S2: $^{13}$C NMR spectrum of the complex 2; Figure S3: IR spectrum of the complex $\Lambda(R,R)$ recorded in CH$_2$Cl$_2$; Figure S4: UV-vis spectrum of the complex $\Lambda(R,R)$ recorded in CH$_2$Cl$_2$; Figure S5: X-ray structure of the Co(III) complex $\Lambda$ of $\Delta$-configuration with co-crystallized acetonitrile molecules; Table S1: Crystallographic data for the complex 2; Table S2: Selected bond distances and angles for the complex 2; Scheme S1: Epoxidation of chalcone; Scheme S2: Kinetic resolution of chalcone epoxide with CO$_2$; Scheme S3: Asymmetric Henry reaction of the o-nitrobenzaldehyde with the nitromethane; Scheme S4: Michael addition of dimethyl malonate to trans-$\beta$-nitrostyrene.

**Author Contributions:** Conceptualization, V.A.L., Y.N.B. and V.I.M.; methodology and experiments, T.F.S. and O.V.K.; data curation, T.F.S., V.A.L., A.F.S., I.V.F. and V.I.M.; writing—Original draft preparation, O.V.K., I.V.F. and V.A.L.; writing—Review and editing, V.A.L., Y.N.B. and V.I.M.; funding acquisition, V.A.L. and V.I.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work has been supported by the Russian Foundation for Basic Research (RFBR grant number 19-03-00659) and the Council of the President of the Russian Federation (grant number MK-3343.2019.3).

**Institutional Review Board Statement:** Not applicable.

**Data Availability Statement:** Data is contained within the article or Supplementary Material.

**Acknowledgments:** XRD study was performed with financial support from the Ministry of Science and Higher Education of the Russian Federation using the equipment of the Center for Molecular Composition Studies of INEOS RAS. The publication has been supported by the RUDN University Strategic Academic Leadership Program (optical rotation measurements). The authors are grateful to Kirill K. Babievsky for CD spectra record and to Aleksei A. Titov for IR- and UV-vis spectra collection.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Gong, L.; Chen, L.-A.; Meggers, E. Asymmetric catalysis Mmediated by the ligand sphere of octahedral chiral-at-metal complexes. Angew. Chem. Int. Ed. 2014, 53, 10868–10874. [CrossRef] [PubMed]
2. Ghosh, S.K.; Ehnbom, A.; Lewis, K.G.; Gladysz, J.A. Hydrogen bonding motifs in structurally characterized salts of the tris(ethylenediamine) cobalt trication, [Co(en)$_3$]$^{3+}$; An interpretive review, including implications for catalysis. Coord. Chem. Rev. 2017, 350, 30–48. [CrossRef]
3. Cruchter, T.; Larionov, V.A. Asymmetric catalysis with octahedral stereogenic-at-metal complexes featuring chiral ligands. Coord. Chem. Rev. 2018, 376, 95–113. [CrossRef]
4. Wegener, A.R.; Kabes, C.Q.; Gladysz, J.A. Launching Werner complexes into the modern era of catalytic enantioselective organic synthesis. Acc. Chem. Res. 2020, 53, 2299–2313. [CrossRef]
5. Ganzmann, C.; Gladysz, J.A. Phase transfer of enantiopure Werner cations into organic solvents: An overlooked family of chiral hydrogen bond donors for enantioselective catalysis. Chem. Eur. J. 2008, 14, 5397–5400. [CrossRef]
6. Belokon, Y.N.; Larionov, V.A.; Mkrtchyan, A.F.; Krustalev, V.N.; Nijland, A.; Saghian, A.S.; Godovikov, I.A.; Peregudov, A.S.; Babievsky, K.K.; Ikonnikov, N.S.; et al. A novel type of catalysts for the asymmetric C-C bond formation based on chiral sterochemically inert cationic Co$^{III}$ complexes. Russ. Chem. Bull. 2012, 61, 2252–2260. [CrossRef]
7. Chen, L.-A.; Xu, W.; Huang, B.; Ma, J.; Wang, L.; Xi, J.; Harms, K.; Gong, L.; Meggers, E. Asymmetric catalysis with an inert chiral-at-metal iridium complex. J. Am. Chem. Soc. 2013, 135, 10598–10601. [CrossRef]
8. Belokon, Y.N.; Maleev, V.I.; North, M.; Larionov, V.A.; Savel’Yeva, T.F.; Nijland, A.; Nelyubina, Y.V. Chiral octahedral complexes of Co$^{III}$ as a family of asymmetric catalysts operating under phase transfer conditions. ACS Catal. 2013, 3, 1951–1955. [CrossRef]
9. Chen, L.-A.; Tang, X.; Xi, J.; Xu, W.; Gong, L.; Meggers, E. Chiral-at-metal octahedral iridium catalyst for the asymmetric construction of an all-carbon quaternary stereocenter. Angew. Chem. Int. Ed. 2013, 52, 14021–14025. [CrossRef]
10. Maleev, V.I.; North, M.; Larionov, V.A.; Fedyanin, I.V.; Savel'yeva, T.F.; Moskalenko, M.A.; Smolyakov, A.F.; Belokon, Y.N. Chiral octahedral complexes of cobalt(III) as “organic catalysts in disguise” for the asymmetric addition of a glycine Schiff base ester to activated olefins. *Adv. Synth. Catal.* 2014, 356, 1803–1810. [CrossRef] 

11. Ma, J.; Ding, X.; Hu, Y.; Huang, Y.; Gong, L.; Meggers, E. Metal-templated chiral Brønsted base organocatalysis. *Nat. Commun.* 2014, 5, 4531. [CrossRef] [PubMed] 

12. Mukherjee, T.; Ganzmann, C.; Bhuvanesh, N.; Gladysz, J.A. Syntheses of enantiopure bifunctional 2-guanidinobenzimidazole cyclopentadienyl ruthenium complexes: Highly enantioselective organometallic hydrogen bond donor catalysts for carbon–carbon bond forming reactions. *Organometallics* 2014, 33, 6723–6737. [CrossRef] 

13. Larionov, V.A.; Markelova, E.P.; Smol'Yakov, A.F.; Savel'yeva, T.F.; Maleev, V.I.; Belokon, Y.N. Chiral octahedral complexes of Co(III) as catalysts for asymmetric epoxidation of chalcones under phase transfer conditions. *RSC Adv.* 2015, 5, 77264–77271. [CrossRef] 

14. Ding, X.; Lin, H.; Gong, L.; Meggers, E. Enantioselective sulfa-Michael addition to α,β-unsaturated γ-oxoesters catalyzed by a metal-templated chiral Brønsted base. *Asian J. Org. Chem.* 2015, 4, 434–437. [CrossRef] 

15. Hu, Y.; Zhou, Z.; Gong, L.; Meggers, E. Asymmetricaza-Henry reaction to provide oxindoles with quaternary carbon stereocenter catalyzed by a metal-templated chiral Brønsted base. *Org. Chem. Front.* 2015, 2, 968–972. [CrossRef] 

16. Liu, J.; Gong, L.; Meggers, E. Asymmetric Friedel–Crafts alkylation of indoles with 2-nitro-3-arylacrylates catalyzed by a metal-templated hydrogen bonding catalyst. *Tetrahedron Lett.* 2015, 56, 4653–4656. [CrossRef] 

17. Lewis, K.G.; Ghosh, S.K.; Bhuvanesh, N.; Gladysz, J.A. Cobalt(III) Werner complexes with 1,2-diphenylethylenediamine ligands: Readily available, inexpensive, and modular chiral hydrogen bond donor catalysts for enantioselective organic synthesis. *ACS Cent. Sci.* 2015, 1, 50–56. [CrossRef] 

18. Rulev, Y.A.; Larionov, V.A.; Lokutova, A.V.; Moskalenko, M.A.; Lependina, O.L.; Maleev, V.I.; North, M.; Belokon, Y.N. Chiral cobalt(III) complexes as bifunctional Brønsted acid-Lewis base catalysts for the preparation of cyclic organic carbonates. *ChemSusChem* 2015, 8, 216–222. [CrossRef] 

19. Xu, W.; Arieno, M.; Löw, H.; Huang, K.; Xie, X.; Cructher, T.; Ma, Q.; Xi, J.; Huang, B.; Wiest, O.; et al. Metal-templated design: Enantioselective hydrogen-bond-driven catalysis requiring only parts-per-million catalyst loading. *J. Am. Chem. Soc.* 2016, 138, 8774–8780. [CrossRef] 

20. Huang, K.; Ma, Q.; Shen, X.; Gong, L.; Meggers, E. Metal-templated asymmetric Catalysis: (Z)-1-bromo-1-nitrostyrenes as versatile substrates for Friedel-Crafts alkylation of indoles. *Asian J. Org. Chem.* 2016, 5, 1198–1203. [CrossRef] 

21. Ma, Q.; Gong, L.; Meggers, E. Enantioselective β-alkylation of pyrroles with the formation of an all-carbon quaternary stereocenter. *Org. Chem. Front.* 2016, 3, 1319–1325. [CrossRef] 

22. Xu, W.; Shen, X.; Ma, Q.; Gong, L.; Meggers, E. Restricted conformation of a hydrogen bond mediated catalyst enables the highly efficient enantioselective construction of an all-carbon quaternary stereocenter. *ACS Catal.* 2016, 6, 7641–7646. [CrossRef] 

23. Ding, X.; Tian, C.; Hu, Y.; Gong, L.; Meggers, E. Tuning the basicity of a metal-templated Brønsted base to facilitate the enantioselective sulfa-Michael addition of aliphatic thiols to α,β-unsaturated N-acylpyrazoles. *Eur. J. Org. Chem.* 2016, 887–890. [CrossRef] 

24. Ghosh, S.K.; Ganzmann, C.; Bhuvanesh, N.; Gladysz, J.A. Werner complexes with ω-dimethylaminoalkyl substituted ethylenediamine ligands: Bifunctional hydrogen-bond-donor catalysts for highly enantioselective Michael additions. *Angew. Chem. Int. Ed.* 2016, 55, 4356–4360. [CrossRef] 

25. Kumar, A.; Ghosh, S.K.; Gladysz, J.A. Tris(1,2-diphenylethylenediamine)cobalt(III) complexes: Chiral hydrogen bond donor catalysts for enantioselective α-aminations of 1,3-dicarbonyl compounds. *Org. Lett.* 2016, 18, 760–763. [CrossRef] 

26. Larionov, V.A.; Peregudova, S.M.; Maleev, V.I.; Belokon, Y.N. A novel type of catalysts for asymmetric oxidative coupling of 2-naphthol. *Russ. Chem. Bull.* 2016, 65, 685–688. [CrossRef] 

27. Joshi, H.; Ghosh, S.K.; Gladysz, J.A. Enantioselective additions of stabilized carbanions to imines generated from α-amido sulfones by using lipophilic salts of chiral tris(1,2-diphenylethylenediamine) cobalt(III) trications as hydrogen bond donor catalysts. *Synthesis 2017*, 49, 3905–3915. [CrossRef] 

28. Gugkvaeva, Z.T.; Larionov, V.A.; Moskalenko, M.A.; Khristaley, V.N.; Nelyubina, Y.V.; Peregudov, A.S.; Tsaloev, A.T.; Maleev, V.I.; Belokon, Y.N. Economical synthesis of α-amino acids from a novel family of easily available Schiff bases of glycine esters and 2-hydroxybenzophenone. *Synthesis 2018*, 51, 607–616. [CrossRef] 

29. Maximuck, W.J.; Gladysz, J.A. Lipophilic chiral cobalt (III) complexes of hexaamine ligands: Efficacies as enantioselective hydrogen bond donor catalysts. *Mol. Catal.* 2019, 473, 110360. [CrossRef] 

30. Kubes, C.Q.; Maximuck, W.J.; Ghosh, S.K.; Kumar, A.; Bhuvanesh, N.S.; Gladysz, J.A. Chiral tricationic tris(1,2-diphenylethylenediamine) cobalt(III) hydrogen bond donor catalysts with defined carbon/metal configurations; matched/mismatched effects upon enantioselectivities with enantiomeric chiral counter anions. *ACS Catal.* 2020, 10, 3249–3263. [CrossRef] 

31. Maximuck, W.J.; Ganzmann, C.; Alvi, S.; Hooda, K.R.; Gladysz, J.A. Rendering classical hydrophilic enantiopure Werner salts [M(en)]nX− lipophilic (M/n = Cr/3, Co/3, Rh/3, Ir/3, Pt/4); new chiral hydrogen bond donor catalysts and enantioselectivities as a function of metal and charge. *Dalton Trans.* 2020, 49, 3680–3691. [CrossRef] [PubMed]
32. Luu, Q.H.; Gladysz, J.A. An air- and water-stable hydrogen-bond-donor catalyst for the enantioselective generation of quaternary carbon stereocenters by additions of substituted cyanooacetate esters to acetylenic esters. *Chem. Eur. J.* 2020, 26, 10230–10239. [CrossRef] [PubMed]

33. Wittitsuwanakul, T.; Mukherjee, T.; Hall, M.B.; Gladysz, J.A. Computational investigations of enantioselection in carbon-carbon bond forming reactions of ruthenium guanidinobenzimidazole second coordination sphere hydrogen bond donor catalysts. *Organometallics* 2020, 39, 1149–1162. [CrossRef]

34. Mukherjee, T.; Ghosh, S.K.; Wittitsuwanakul, T.; Bhuvanesh, N.; Gladysz, J.A. Chiral-at-metal ruthenium complexes with guanidinobenzimidazole and pentaphenylcyclopentadienyl ligands: Synthesis, resolution, and preliminary screening as enantioselective second coordination sphere hydrogen bond donor catalysts. *Organometallics* 2020, 39, 1163–1175. [CrossRef]

35. Belokon’, Y.N.; Bul’chev, A.G.; Maleev, V.I.; North, M.; Mal’fanov, I.L.; Ivanov, N.S. Asymmetric synthesis of cyanohydrins catalysed by a potassium $\Delta$-bis[N-salicylidene-(R)-tryptophanato]cobaltate complex. *Mendeleev Commun.* 2004, 14, 249–250. [CrossRef]

36. Belokon’, Y.N.; Maleev, V.I.; Mal’fanov, I.L.; Savel’eva, T.F.; Bul’chev, A.G.; Usanov, D.L.; Kataev, D.A.; North, M. Anionic chiral cobalt(III) complexes as catalysts of asymmetric synthesis of cyanohydrins. *Russ. Chem. Bull.* 2006, 55, 821–827. [CrossRef]

37. Belokon’, Y.N.; Maleev, V.I.; Mal’fanov, I.L.; Savel’eva, T.F.; Kataev, D.A.; North, M. Asymmetric synthesis of cyanohydrins catalysed by a potassium $\Delta$-bis[N-salicylidene-(R)-tryptophanato]cobaltate complex. *Tetrahedron* 2008, 64, 821–827. [CrossRef]

38. Belokon’, Y.N.; Kataev, D.A.; Saveleva, T.F.; Skrupskaya, T.V.; Lyssenko, K.A.; Godovikov, I.A.; et al. Potassium and silver chiral cobaltate(III) complexes as precatalysts for asymmetric C-C bond formation. *Tetrahedron: Asymmetry* 2009, 20, 1746–1752. [CrossRef]

39. Huo, H.; Fu, C.; Wang, C.; Harms, K.; Meggers, E. Metal-templated enantioselective enamine/H-bonding dual activation catalysis. *Chem. Commun.* 2014, 50, 10409–10411. [CrossRef]

40. Yu, J.; Jiang, H.-J.; Zhou, Y.; Luo, S.-W.; Gong, L.-Z. Sodium salts of anionic chiral cobalt(III) complexes as catalysts of the enantioselective Povarov reaction. *Angew. Chem. Int. Ed.* 2015, 54, 11209–11213. [CrossRef]

41. Cruchtter, T.; Medvedev, M.G.; Shen, X.; Mietke, T.; Harms, K.; Marsch, M.; Meggers, E. Asymmetric nucleophilic catalysis with an octahedral chiral-at-metal iridium(III) complex. *ACS Catal.* 2017, 7, 5151–5162. [CrossRef]

42. Jiang, H.-J.; Liu, K.; Yu, J.; Zhang, L.; Gong, L.-Z. Switchable stereoselectivity in bromoaminoacylation of olefins: Using Brønsted acids of anionic chiral cobalt(III) complexes. *Angew. Chem. Int. Ed.* 2017, 56, 11931–11935. [CrossRef] [PubMed]

43. Jiang, H.-J.; Liu, K.; Wang, J.; Li, N.; Yu, J. Brønsted acids of anionic chiral Co(III) complexes as catalysts for the stereoselective synthesis of cis-4-aminofuranobenzopyrans. *Org. Biomol. Chem.* 2017, 15, 9077–9080. [CrossRef] [PubMed]

44. Liu, K.; Jiang, H.-J.; Li, N.; Li, H.; Wang, J.; Zhang, Z.; Yu, J. Enantioselective bromoaminoacylation of tryptamines induced by chiral Co(III)-complex-templated Brønsted acids under an air atmosphere. *J. Org. Chem.* 2018, 83, 6815–6823. [CrossRef] [PubMed]

45. Li, N.; Yu, H.; Wang, R.; Shen, J.; Wu, W.-Q.; Liu, K.; Sun, T.-T.; Zhang, Z.; Yao, C.-Z.; Yu, J. Enantioselective intermolecular iodoacetalization of enol ethers catalysed by chiral Co(III)-complex-templated Brønsted acids. *Tetrahedron Lett.* 2018, 59, 3605–3608. [CrossRef]

46. Wang, R.; Wu, W.-Q.; Li, N.; Shen, J.; Liu, K.; Yu, J. Brønsted acids of anionic chiral cobalt(III) complexes as catalysts for the iodoglycosylation or iodoacetylation of glycals. *Synlett* 2019, 30, 1077–1084. [CrossRef]

47. Skubi, K.L.; Kidd, J.B.; Jung, H.; Geuzé, I.A.; Baik, M.-H.; Yoon, T.P. Enantioselective excited-state photoreactions controlled by a chiral hydrogen-bonding iridium sensitizer. *J. Am. Chem. Soc.* 2017, 139, 17186–17192. [CrossRef]

48. Zheng, J.; Swords, W.B.; Jung, H.; Skubi, K.L.; Kidd, J.B.; Meyer, G.J.; Baik, M.-H.; Yoon, T.P. Enantioselective intermolecular excited-state photoreactions using a chiral Ir triplet sensitizer: Separating association from energy transfer in asymmetric photocatalysis. *J. Am. Chem. Soc.* 2019, 141, 13625–13634. [CrossRef]

49. Brunner, H. Optically active organometallic compounds of transition elements with chiral metal atoms. *Angew. Chem. Int. Ed.* 1999, 38, 1194–1208. [CrossRef]

50. Fontecave, M.; Hamelin, O.; Ménage, S. Chiral-at-metal complexes as asymmetric Catalysts. *Chiral Diazaligands Asymmetric Synth.* 2005, 15, 271–288. [CrossRef]

51. Zhang, L.; Meggers, E. Stereogenic-only-at-metal catalytic systems. *Chem. Asian J.* 2017, 12, 2335–2342. [CrossRef]

52. Emelyanov, M.A.; Stolotova, N.V.; Lisov, A.A.; Medvedev, M.G.; Smolyakov, A.F.; Maleev, V.I.; Larionov, V.A. Fixation of CO$_2$ with epoxides at ambient conditions catalyzed by a sustainable bifunctional metal-templated hydrogen bond donor catalyst. *J. CO$_2$ Util.* 2021. [under review]

53. Reed, A.E.; Weinstock, R.B.; Weinhold, F. Natural population analysis. *J. Chem. Phys.* 1985, 83, 735–746. [CrossRef]

54. Breneman, C.M.; Wiberg, K.B. Determining atom-centered monopoles from molecular electrostatic potentials. The need for high sampling density in formamide conformational analysis. *J. Comput. Chem.* 1990, 11, 361–373. [CrossRef]

55. Kano, T.; Hato, Y.; Maruoka, K. Design of a C$_2$-symmetric chiral pyrrolidine-based amino sulfonamide: Application to anti-selective direct asymmetric Mannich reactions. *Tetrahedron Lett.* 2006, 47, 8467–8469. [CrossRef]

56. Sheldrick, G.M. SHELXT – Integrated space-group and crystal-structure determination. *Acta Cryst.* 2015, A71, 3–8. [CrossRef]

57. Sheldrick, G.M. Crystal structure refinement with SHELXL. *Acta Cryst.* 2015, C71, 3–8. [CrossRef]
58. Dolomanov, O.V.; Bourhis, L.J.; Gildea, R.J.; Howard, J.A.K.; Puschmann, H. OLEX2: A complete structure solution, refinement and analysis program. *J. Appl. Crystallogr.* 2009, 42, 339–341. [CrossRef]

59. Neese, F. The ORCA program system. *Wiley Interdiscip. Rev. Comput. Mol. Sci.* 2012, 2, 73–78. [CrossRef]

60. Adamo, C.; Barone, V. Toward reliable density functional methods without adjustable parameters: The PBE0 model. *J. Chem. Phys.* 1999, 110, 6158–6170. [CrossRef]

61. Grimme, S.; Ehrlich, S.; Goerigk, L. Effect of the damping function in dispersion corrected density functional theory. *J. Comput. Chem.* 2011, 32, 1456–1465. [CrossRef] [PubMed]

62. Weigend, F.; Ahlrichs, R. Balanced basis sets of split valence, triple zeta valence and quadruple zeta valence quality for H to Rn: Design and assessment of accuracy. *Phys. Chem. Chem. Phys.* 2005, 7, 3297–3305. [CrossRef] [PubMed]

63. Nikolaienko, T.Y.; Bulavin, L.A.; Hovorun, D.M. JANPA: An open source cross-platform implementation of the Natural Population Analysis on the Java platform. *Comput. Theor. Chem.* 2014, 1050, 15–22. [CrossRef]

64. Lu, T.; Chen, F. Multiwfn: A multifunctional wavefunction analyzer. *J. Comput. Chem.* 2012, 33, 580–592. [CrossRef] [PubMed]