Highly Efficient Tetranuclear $Zn^{II}_2Ln^{III}_2$ Catalysts for the Friedel–Crafts Alkylation of Indoles and Nitrostyrenes

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Abstract: We demonstrate for the first time the high efficacy of tetranuclear $Zn^{II}_2Ln^{III}_2$ coordination clusters (CCs) as catalysts for the Friedel–Crafts (FC) alkylation of indoles with a range of *trans*-β-nitrostyrenes. The reaction proceeds in good to excellent yields (76%–99%) at room temperature with catalyst loadings as low as 1.0 mol %.

1. Introduction

The Friedel–Crafts (FC) reaction of aromatic compounds with electron-deficient alkenes is used widely in synthetic organic chemistry [1,2]. The reaction between indole and β-nitrostyrene is important as it gives access to indole-based alkaloids such as melatonin analogues (**A**), 1,2,3,4-tetrahydro-β-carbolines (THBCs, (**B**)), and "triptans" (**C**) (Scheme 1) [3,4].
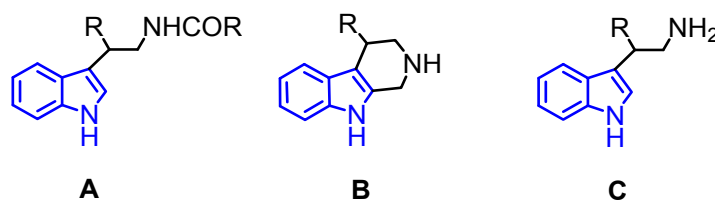

Scheme 1. Versatile intermediates in organic synthesis derived from Indolylnitroalkanes.

Nitroalkenes have received considerable attention as active Michael acceptors [5] because the nitro derivatives can be transformed into amino compounds with a variety of different functionalities [6–10]. For the reaction between indole and β-nitrostyrene, various catalytic systems have been proposed. These include hydrogen-bond-based compounds [11–16] such as thiourea [11,14,15,17–20], phosphoric acid [16], silanediols [21,22], sulfamic acid [23] and 2,6-bis(amido)benzoic acid [24]; metal based compounds [25–41] such as Al^{III} [25,39], Cu^{II} [26–30,41], Zn^{II} [31–35,40,42], Fe^{III} [36], Pd^{II} [37], Rh^{II} [43,44] and SmI_3 [38]; and heterogeneous systems including metal organic frameworks, [45,46] nano n-propylsulfonated $\gamma\text{-}Fe_2O_3$ (NPS-γ-Fe_2O_3) [47] and zeolite HY [48]. However efficient metal catalytic systems for this transformation are very rare. Du [49–53] developed an efficient catalyst containing bisoxazolines and bisimidazolines-Zn(OTf)$_2$. Wang reported the involvement of a dimeric Cu^{II} coordination cluster (CC) and piperidine as a catalyst for reactions between aromatic nitroalkenes and ortho-substituted indoles [41]. However, some of

the reported protocols have drawbacks such as high catalyst loading, long reaction time, the need for additives, low temperature (0 to −20 °C) and multi-step designed ligands, thus limiting their practical applications.

In **3d/4f** chemistry, only a few polynuclear CCs have been successfully used as homogenous catalysts [54–56]. We recently initiated a project on the synthesis of **3d/4f** CCs stabilized by the Schiff base organic ligand H2L [(*E*)-(2-hydroxy-3-methoxybenzylidene-amino)phenol], that would display catalytic properties [57–59]. We also reported the synthesis and characterisation of a series of isoskeletal [60] tetranuclear $Zn^{II}_2Ln^{III}_2$ CCs formulated as $[Zn^{II}_2Ln^{III}_2L_4(NO_3)_2(DMF)_2]$ (**1Ln**) where Ln is Y (**1Y**), Sm (**1Sm**), Eu (**1Eu**) Gd (**1Gd**), Dy (**1Dy**), Tb (**1Tb**) and Yb (**1Yb**) possessing a defect dicubane topology (Figure 1). These compounds can be synthesized quantitatively in two steps, up to multigram scale and are air stable for a few months. We showed that these bimetallic species remain intact in organic and aqueous solutions, by ESI-MS studies, EPR studies for **1Gd** and NMR studies for **1Y** analogues. This precise topology shows that the Zn and the Ln centres are very close (approximately 3.3 Å), permitting both metals to coordinate to the substrates and promote the coupling reaction. Compounds **1Y** and **1Dy** showed high efficiency as catalysts, at room temperature, with low catalytic loadings in FC alkylation of indole with aldehydes leading to bis-indolylmethane derivatives [59]. A study of the suitability of **1Ln** as catalysts in FC alkylation of indole with nitrostyrene is presented herein.
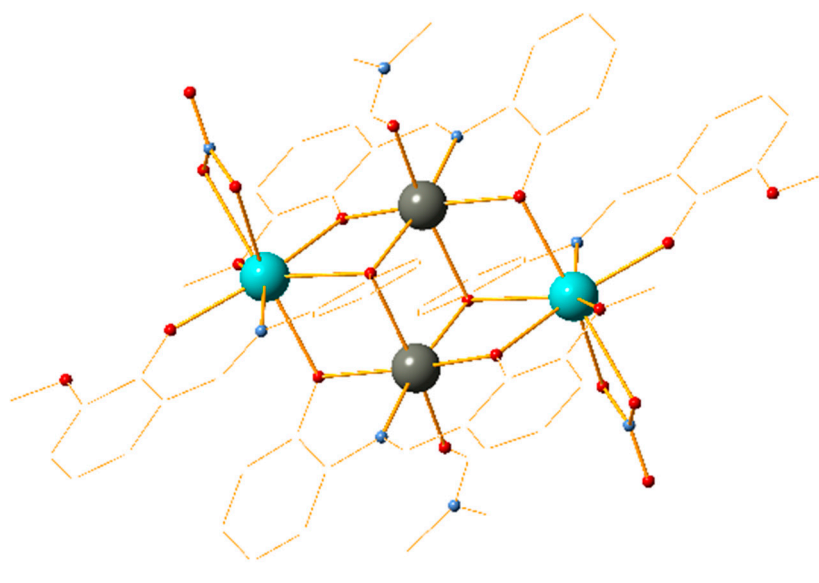

Figure 1. Molecular structure of **1Ln**. Colour code: Zn^{II}: grey; Ln^{III}: light blue; O: red; N: blue. C and H atoms are omitted for clarity.

2. Results

The first step was to optimize the reaction conditions for the alkylation of indole. We screened several reaction parameters, such as the use of different catalysts (Table 1, entries 1–9), solvents (Table 1, entries 10–14), temperature (Table 1, entries 15–17) and catalyst loading (Table 1, entries 18–20). We studied the reaction between indole (0.50 mmol) **2** and nitroalkene (0.50 mmol) **3** in EtOH at room temperature and a catalyst loading of 1.0 mol % (Table 1 entries 1–9). A blank experiment in the absence of the **3d/4f** CCs catalyst showed no conversion (Table 1, entry 1) and very low conversions were obtained in the presence of Dy or Zn salts (Table 1, entries 2–3). The reactions with **1Dy** and **1Y** after 24 h show very high yields, 99% and 94%, respectively. (Table 1, entries 4–5). Other catalysts such as **1Eu**, **1Gd**, **1Nd** and **1Tb** showed lower yields (Table 1, entries 1–6). Therefore, **1Dy** was the best choice for this FC reaction. We then decided to identify the influence of the solvent on the catalytic performance. Our catalyst showed high activity in ethanol with 99% yield of the desired product **4a**

(Table 1, entry 4). Solvents such as THF, water, acetonitrile and *N,N'*-dimethylformamide (DMF) had a negative influence on the catalytic activity; therefore, ethanol was the best choice for further studies. At room temperature, the yield of **4a** was 99%, but only 5% at 0 °C. Lower yields were obtained at 60 °C (Table 1, entry 18), so the following reactions were made at this temperature. As shown in Table 1, it was sufficient to use a catalyst loading of 1.0 mol % to obtain a yield up to 99% (Table 1, entry 4). An increase of the catalyst loading from 1.0 mol % to 5 mol % led to a remarkable decrease in the yield of the desired product **4a** (Table 1, entries 19–20). This finding can be explained due to the low solubility of the catalyst. Further, a decrease in the catalyst loading to 0.5 mol % also showed lower yield of the desired product **4a** (Table 1, entry 18). Therefore, we used 1.0 mol % **1Dy** in ethanol at room temperature for further experiments.

Table 1. Optimization of the Friedel–Crafts Alkylation of Indole **2a** with *trans*-β-Nitrostyrene **3a** Catalyzed by **1Ln** Complexes [a].
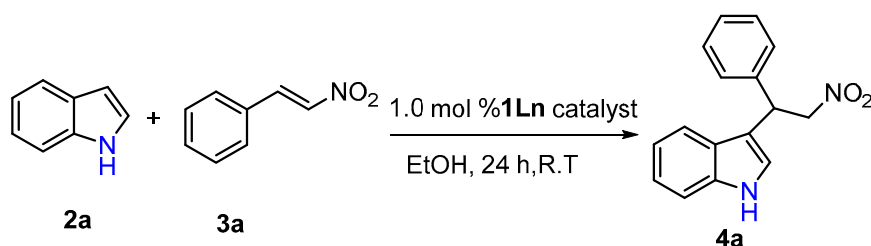
Entry	Catalyst	Yield (%) [b]
1	none	0
2	Dy (OTf)$_3$	8
3	Zn (OTf)$_2$	20
4	**1Dy**	99
5	**1Y**	94
6	**1Eu**	55
7	**1Gd**	30
8	**1Nd**	12
9	**1Tb**	24
10	**1Dy** (Toluene)	30
11	**1Dy** (Water)	0
12	**1Dy** (THF)	0
13	**1Dy** (Acetonitrile)	0
14	**1Dy** (DMF)	5
15	**1Dy** (−30 °C)	0
16	**1Dy** (0 °C)	5
17	**1Dy** (60 °C)	30
18	**1Dy** (0.5%)	26
19	**1Dy** (2.5%)	62
20	**1Dy** (5.0%)	17

[a] Reaction conditions: indole **2a** (0.50 mmol), *trans*-β-nitrostyrene **3a** (0.50 mmol) in 3 mL of EtOH under 1.0 mol % **1Ln** complexes; [b] Isolated yield by column chromatography.

To explore the scope of the reaction, various nitroalkenes were treated with indole (Table 2). In the first experiments *R'* was aromatic (Table 2, entries 1–8). Several catalytic systems gave slightly lower yields due to the electronic effect of *para* substitution of the phenyl group of aromatic nitroalkenes. In all these cases, very good yields were obtained, ranging from 92% for the 4-fluoro substrate **4d** to 98% for the tolyl substituted compound **4b**. A slight improvement of the yield up to 99% was observed by use of a heteroaromatic nitroalkene bearing a furan substituent (entry 8). The effect of substitution of the indole is also shown in Table 2 (entries 9–15). The substituent at position 5 of the indole had little effect on yield except for the electron-drawing group (–NO$_2$) (Table 2, entry 12).

Table 2. Scope of the Friedel–Crafts (FC) alkylation of Indoles with various nitro-styrenes catalysed by **1Dy** [a].

Entry	R^1	R^2	Yield (%) [b]
1	H	Ph	99 (**4a**)
2	H	4-Me-Ph	98 (**4b**)
3	H	4-MeO-Ph	96 (**4c**)
4	H	4-F-Ph	92 (**4d**)
5	H	4-Br-Ph	94 (**4e**)
6	H	2-furan	99 (**4f**)
7	OMe	Ph	97 (**4g**)
8	Br	Ph	95 (**4h**)
9	I	Ph	94 (**4i**)
10	NO_2	Ph	76 (**4j**)
11	$OCH_2C_6H_5$	Ph	96 (**4k**)
12	OMe	2-furan	98 (**4l**)
13	Br	2-furan	95 (**4m**)
14	$OCH_2C_6H_5$	2-furan	96 (**4n**)
15	I	2-furan	95 (**4o**)

[a] Reaction conditions: indole **2** (0.50 mmol) with *trans*-β-nitrostyrene **3** (0.50 mmol) in 3 mL of EtOH under 1.0 mol % **1Dy** complex; [b] Isolated yield by column chromatography.

Further, we investigated the reaction of *N*-alkylated and 2-methyl indole with various nitrostyrenes. The results are summarized in Table 3. The products were isolated in good to excellent yields (Table 3, entries 1–10). A change of the substituent at the nitrogen atom in **5**, and at position 2 of the indole did not show any profound effect on the yield of the desired product (99%, Table 3, entries 1 and 6). Compound **6h** was characterized via single crystal X-ray crystallography (see Figure S1).

Table 3. Friedel–Crafts Alkylation of *N*-alkylated and 2-methyl Indoles with Various Nitroalkenes [a].

Entry	R^1	R^3	R^2	Yield (%) [b]
1	CH_3	H	Ph	99 (**6a**)
2	CH_3	H	4-MeO-Ph	99 (**6b**)
3	CH_3	H	4-F-Ph	93 (**6c**)
4	CH_3	H	4-Br-Ph	95 (**6d**)
5	CH_3	H	2-furanyl	99 (**6e**)
6	H	CH_3	Ph	99 (**6f**)
7	H	CH_3	4-F-Ph	94 (**6g**)
8	H	CH_3	4-Br-Ph	96 (**6h**)
9	H	CH_3	2-furanyl	99 (**6i**)
10	H	CH_3	4-Me-Ph	98 (**6j**)

[a] Reaction conditions: indole 5 (0.3 mmol), *trans*-β-nitrostyrene 3 (0.3 mmol), 3 mL of EtOH, 1.0 mol % 1Dy complex; [b] Isolated yield by column chromatography.

The substrate binding of *trans*-β-nitrostyrene **3a** by **1Dy** was investigated by UV-Vis spectroscopy in a water/ethanol solution. A 0.1 mM solution *trans*-β-nitrostyrene **3a** exhibited a strong absorption at 320 nm. The **1Dy** was added to the solution and absorption was recorded over 3 h with 5 min intervals between measurements. It was observed (Figure S2) that the intensities of the peak at 320 nm gradually decreased. The quenching of band may be attributed to the bonding of nitrostyrene with **1Dy** through weak Van der Waals interactions. Similar quenching was observed with the indole substrate (Figure S3), indicating the binding behaviour of both substrates to **1Dy**. Thus both substrates can be activated after coordination with the two metal centres in **1Dy** which favours the conjugate addition of the nucleophiles. Similar studies were conducted with $Zn(OTf)_2$ and $Dy(OTf)_3$ to determine the preference of each substrate for the Ln^{III} or Zn^{II} metal centres. In **3a** a greater rate of quenching with $Dy(OTf)_3$ than $Zn(OTf)_2$ is shown, whereas with **2a** the rates are similar. This may suggest that **3a** preferentially binds to the Dy^{III} centre. The **1Dy** catalyst for both substrates demonstrates a greater rate of quenching than either $Zn(OTf)_2$ or $Dy(OTf)_2$, perhaps indicating a stronger interaction with the metal centres in tandem. Based on the above results and the crystal structure of **1Dy** [59] in which a nitrate group chelates to Dy (*trans*-β-nitrostyrene can be considered as an alternative to nitrate), a plausible mechanism and transition state can be proposed shown in Scheme 2. We envision that the nitroalkenes are activated by chelation to Dy^{III} [44] and π–π stacking between the phenyl group of the coordinating ligand L and the phenyl group of nitroalkenes. In addition, the indole substrate will bond to the Zn^{II} through the nitrogen atom and bring the two organic moieties efficiently close to favour the formation of the alkylated product.

(a)

(b)
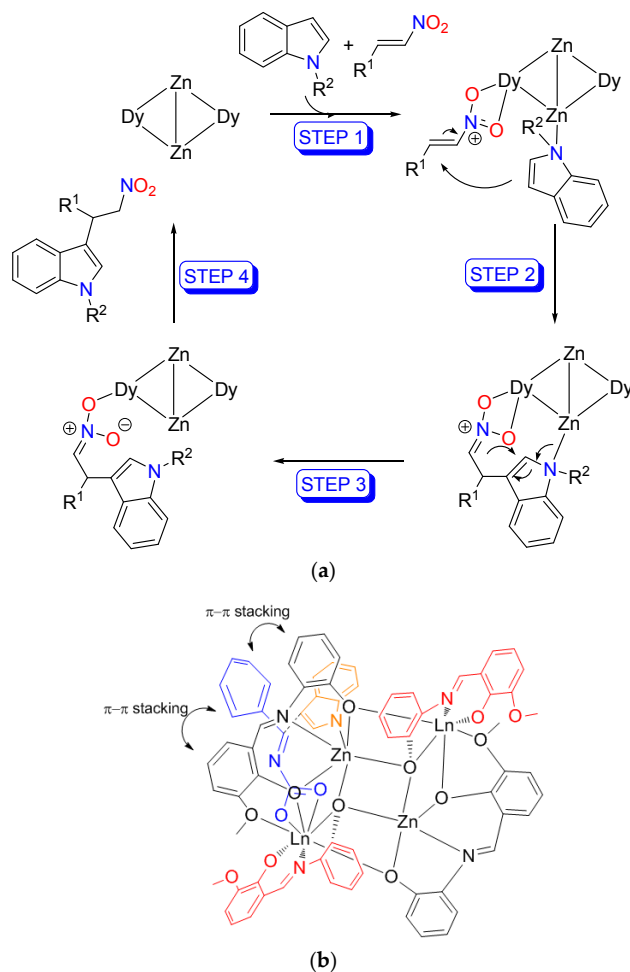
Scheme 2. (**a**) A plausible mechanism for the FC alkylation; (**b**) Proposed transition state model of catalyst.

3. Discussion

We report herein, for the first time, a highly efficient, tetranuclear **3d/4f** catalytic system for the FC alkylation of indoles with nitroalkenes. The reaction performs very well over a range of nitroalkenes and indoles, especially those with substituents in the para position. Products are obtained with a yield of up to 98% at room temperature and with only 1% catalyst loading, showcasing the efficacy of these catalytic species. Further exploration of the mechanism of this specific reaction, the involvement of chiral ligands for the synthesis of **3d/4f** CCs and their employment in other asymmetric reactions is currently under way in our laboratory.

4. Materials and Methods

All chemicals and solvents were purchased from Sigma Aldrich, S.D. Fine Chemicals, and commercial suppliers. The progress of the reaction was monitored by thin layer chromatography (TLC) using Merck silica gel 60 F254 plates. Products were purified by column chromatography on silica gel (60–120 mesh). NMR spectra were collected using a Bruker Advance III HD 500 MHz Spectrometer. The ^{1}H and ^{13}C NMR spectroscopic data were analysed with a 500 MHz spectrometer in CDCl$_3$. Chemical shifts are reported in parts per million (δ) relative to tetramethylsilane as internal standard. The coupling constants (*J*) are reported in Hz, and the splitting patterns of the proton signals are described as s (singlet), d (doublet), t (triplet), and m (multiplet).

4.1. Synthesis of Catalysts

All CCs were synthesised according to the literature [59].

4.2. General Procedure for the Friedel–Craft Reaction

All experiments were carried out in the open atmosphere and on a mmol scale. A 10 mL round bottom flask was charged with catalyst **1Dy** (1.0 mol %), nitrostyrene (0.5–0.3 mmol), indole (0.5–0.3 mmol). Solvent (3 mL) was added and the reaction mixture was stirred for 24 h at room temperature. The product was purified by silica gel column chromatography.

4.3. Single Crystal X-Ray Structure Determinations

Crystals suitable for single crystal X-ray diffraction analyses were obtained for compound **6h**. Preliminary data on the space group and unit cell dimensions, as well as intensity data, were collected on an Agilent Xcalibur Eos Gemini Ultra diffractometer with a CCD plate detector, under a flow of nitrogen gas, at 173(2) K using Mo Kα radiation (λ = 0.71073 Å). CRYSALIS CCD and RED software Reflection intensities were corrected for absorption by the multi-scan method. Structure solution and refinement were accomplished using Olex2 [61], solved using either Superflip [62] and refined with SHELXL [63]. The non-hydrogen atoms were refined with anisotropic thermal parameters. Hydrogen atoms were geometrically fixed and allowed to refine using the riding model. Geometric/crystallographic calculations were performed using Olex2 [61], package; graphics were prepared with Crystal Maker [64]. CCDC 1482790.

Author Contributions: P.K. and G.E.K. conceived and designed the experiments; P.K., K.G., S.L. and S.I.S. performed the experiments. G.E.K. Analysed the data and wrote the paper.

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

References

1. Olah, G.A.; Khrisnamurti, R.; Prakash, G.K.S.I. *Comprehensive Organic Synthesis*; Trost, B.M., Fleming, I., Eds.; Pergamon: Oxford, UK, 1991.

2. Roberts, R.M.; Khalaf, A.A. *Friedel–Crafts Alkylation Chemistry: A Century of Discovery*; Marcel, D., Ed.; Marcel Dekker Inc.: New York, NY, USA, 1984.

3. Sundberg, R. *The Chemistry of Indoles*; Academic: New York, NY, USA, 1996.

4. Lancianesi, S.; Palmieri, A.; Petrini, M. Synthetic Approaches to 3-(2-Nitroalkyl) Indoles and Their Use to Access Tryptamines and Related Bioactive Compounds. *Chem. Rev.* **2014**, *114*, 7108–7149. [CrossRef] [PubMed]

5. Berner, O.M.; Tedeschi, L.; Enders, D. Asymmetric Michael additions to nitroalkenes. *Eur. J. Org. Chem.* **2002**, *2002*, 1877–1894. [CrossRef]

6. Ono, N. Synthesis of Heterocyclic Compounds. In *The Nitro Group in Organic Synthesis*; John Wiley & Sons: Hoboken, NJ, USA, 2003.

7. Papadas, I.T.; Fountoulaki, S.; Lykakis, I.N.; Armatas, G.S. Controllable Synthesis of Mesoporous Iron Oxide Nanoparticle Assemblies for Chemoselective Catalytic Reduction of Nitroarenes. *Chem. Eur. J.* **2016**, *22*, 4600–4607. [CrossRef] [PubMed]

8. Fountoulaki, S.; Daikopoulou, V.; Gkizis, P.L.; Tamiolakis, I.; Armatas, G.S.; Lykakis, I.N. Mechanistic studies of the reduction of nitroarenes by $NaBH_4$ or hydrosilanes catalyzed by supported gold nanoparticles. *ACS Catal.* **2014**, *4*, 3504–3511. [CrossRef]

9. Stratakis, M.; Garcia, H. Catalysis by supported gold nanoparticles: Beyond aerobic oxidative processes. *Chem. Rev.* **2012**, *112*, 4469–4506. [CrossRef] [PubMed]

10. Blaser, H.-U.; Steiner, H.; Studer, M. Selective catalytic hydrogenation of functionalized nitroarenes: An update. *ChemCatChem* **2009**, *1*, 210–221. [CrossRef]

11. Herrera, R.P.; Sgarzani, V.; Bernardi, L.; Ricci, A. Catalytic enantioselective Friedel–Crafts alkylation of indoles with nitroalkenes by using a simple thiourea organocatalyst. *Angew. Chem. Int. Ed.* **2005**, *44*, 6576–6579. [CrossRef] [PubMed]

12. Zhuang, W.; Hazell, R.G.; Jørgensen, K.A. Enantioselective Friedel–Crafts type addition of indoles to nitro-olefins using a chiral hydrogen-bonding catalyst-synthesis of optically active tetrahydro-β-carbolines. *Org. Biomol. Chem.* **2005**, *3*, 2566–2571. [CrossRef] [PubMed]

13. Fleming, E.M.; McCabe, T.; Connon, S.J. Novel axially chiral bis-arylthiourea-based organocatalysts for asymmetric Friedel–Crafts type reactions. *Tetrahedron Lett.* **2006**, *47*, 7037–7042. [CrossRef]

14. Li, L.; Ganesh, M.; Seidel, D. Catalytic Enantioselective Synthesis of α,β-Diamino Acid Derivatives. *J. Am. Chem. Soc.* **2009**, *130*, 16464–16465. [CrossRef] [PubMed]

15. Marqués-López, E.; Alcaine, A.; Tejero, T.; Herrera, R.P. Enhanced Efficiency of Thiourea Catalysts by External Brønsted Acids in the Friedel–Crafts Alkylation of Indoles. *Eur. J. Org. Chem.* **2011**, *2011*, 3700–3705. [CrossRef]

16. Itoh, J.; Fuchibe, K.; Akiyama, T. Chiral phosphoric acid catalyzed enantioselective Friedel–Crafts alkylation of indoles with nitroalkenes: Cooperative effect of 3 Å molecular sieves. *Angew. Chem. Int. Ed.* **2008**, *47*, 4016–4018. [CrossRef] [PubMed]

17. So, S.S.; Burkett, J.A.; Mattson, A.E. Internal Lewis acid assisted hydrogen bond donor catalysis. *Org. Lett.* **2011**, *13*, 716–719. [CrossRef] [PubMed]

18. Roca-Lopez, D.; Marques-Lopez, E.; Alcaine, A.; Merino, P.; Herrera, R.P. A Friedel–Crafts alkylation mechanism using an aminoindanol-derived thiourea catalyst. *Org. Biomol. Chem.* **2014**, *12*, 4503–4510. [CrossRef] [PubMed]

19. Turks, M.; Rolava, E.; Stepanovs, D.; Mishnev, A.; Markovi, D. Novel 3-C-aminomethyl-hexofuranose-derived thioureas and their testing in asymmetric catalysis. *Tetrahedron Asymmetry* **2015**, *26*, 952–960. [CrossRef]

20. McGuirk, C.M.; Mendez-Arroyo, J.; Lifschitz, A.M.; Mirkin, C.A. Allosteric Regulation of Supramolecular Oligomerization and Catalytic Activity via Coordination-Based Control of Competitive Hydrogen-Bonding Events. *J. Am. Chem. Soc.* **2014**, *136*, 16594–16601. [CrossRef] [PubMed]

21. Schafer, A.G.; Wieting, J.M.; Mattson, A.E. Silanediols: A new class of hydrogen bond donor catalysts. *Org. Lett.* **2011**, *13*, 5228–5231. [CrossRef] [PubMed]

22. Tran, N.T.; Wilson, S.O.; Franz, A.K. First Catalytic Asymmetric [3+2] allylsilane annulation reaction Cooperative Hydrogen-Bonding Effects in Silanediol Catalysis. *Org. Lett.* **2012**, *14*, 186–189. [CrossRef] [PubMed]

23. An, L.-T.; Zou, J.-P.; Zhang, L.-L.; Zhang, Y. Sulfamic acid-catalyzed Michael addition of indoles and pyrrole to electron-deficient nitroolefins under solvent-free condition. *Tetrahedron Lett.* **2007**, *48*, 4297–4300. [CrossRef]

24. Moriyama, K.; Sugiue, T.; Saito, Y.; Katsuta, S.; Togo, H. 2,6-Bis(amido)benzoic Acid with Internal Hydrogen Bond as Brønsted Acid Catalyst for Friedel–Crafts Reaction of Indoles. *Adv. Synth. Catal.* **2015**, *357*, 2143–2149. [CrossRef]

25. Bandini, M.; Garelli, A.; Rovinetti, M.; Tommasi, S.; Umani-Ronchi, A. Catalytic enantioselective addition of indoles to arylnitroalkenes: An effective route to enantiomerically enriched tryptamine precursors. *Chirality* **2005**, *17*, 522–529. [CrossRef] [PubMed]

26. Singh, P.K.; Bisai, A.; Singh, V.K. Enantioselective Friedel–Crafts alkylation of indoles with nitroalkenes catalyzed by a bis(oxazoline)–Cu(II) complex. *Tetrahedron Lett.* **2007**, *48*, 1127–1129. [CrossRef]

27. Kim, H.Y.; Kim, S.; Oh, K. Orthogonal enantioselectivity approaches using homogeneous and heterogeneous catalyst systems: Friedel–Crafts alkylation of indole. *Angew. Chem. Int. Ed.* **2010**, *49*, 4476–4478. [CrossRef] [PubMed]

28. Arai, T.; Yokoyama, N. Tandem catalytic asymmetric Friedel–Crafts/Henry reaction: Control of three contiguous acyclic stereocenters. *Angew. Chem. Int. Ed.* **2008**, *47*, 4989–4992. [CrossRef] [PubMed]

29. Arai, T.; Yokoyama, N.; Yanagisawa, A. A library of chiral imidazoline–aminophenol ligands: Discovery of an efficient reaction sphere. *Chem. Eur. J.* **2008**, *14*, 2052–2059. [CrossRef] [PubMed]

30. Yokoyama, N.; Arai, T. Asymmetric Friedel–Crafts reaction of *N*-heterocycles and nitroalkenes catalyzed by imidazoline–aminophenol–Cu complex. *Chem. Commun.* **2009**, *22*, 3285–3257. [CrossRef] [PubMed]

31. Jia, Y.; Zhu, S.; Yang, Y.; Zhou, Q.; August, R.V. Asymmetric Friedel−Crafts Alkylations of Indoles with Nitroalkenes Catalyzed by Zn(II)−Bisoxazoline Complexes. *J. Org. Chem.* **2006**, *71*, 75–80. [CrossRef] [PubMed]

32. Guo, F.; Lai, G.; Xiong, S.; Wang, S.; Wang, Z. Monodentate *N*-Ligand-Directed Bifunctional Transition-Metal Catalysis: Highly Enantioselective Friedel–Crafts Alkylation of Indoles with Nitroalkenes. *Chem. Eur. J.* **2010**, *16*, 6438–6441. [CrossRef] [PubMed]

33. Yuan, Z.-L.; Lei, Z.-Y.; Shi, M. BINAM and H^8-BINAM-based chiral imines and Zn(OTf)$_2$-catalyzed enantioselective Friedel–Crafts alkylation of indoles with nitroalkenes. *Tetrahedron Asymmetry* **2008**, *19*, 1339–1346. [CrossRef]

34. Lin, S.; You, T. Synthesis of 9,9′-biphenanthryl-10, 10′-bis (oxazoline)s and their preliminary evaluations in the Friedel–Crafts alkylations of indoles with nitroalkenes. *Tetrahedron* **2009**, *65*, 1010–1016. [CrossRef]

35. McKeon, S.C.; Müller-Bunz, H.; Guiry, P.J. New Thiazoline–Oxazoline Ligands and Their Application in the Asymmetric Friedel–Crafts Reaction. *Eur. J. Org. Chem.* **2009**, *2009*, 4833–4841. [CrossRef]

36. Jalal, S.; Sarkar, S.; Bera, K.; Maiti, S.; Jana, U. Synthesis of Nitroalkenes Involving a Cooperative Catalytic Action of Iron(III) and Piperidine: A One-Pot Synthetic Strategy to 3-Alkylindoles, 2*H*-Chromenes and *N*-Arylpyrrole. *Eur. J. Org. Chem.* **2013**, *2013*, 4823–4828. [CrossRef]

37. Kitanosono, T.; Miyo, M.; Kobayashi, S. The combined use of cationic palladium(II) with a surfactant for the C–H functionalization of indoles and pyrroles in water. *Tetrahedron* **2015**, *71*, 7739–7744. [CrossRef]

38. Zhan, Z.-P.; Yang, R.-F.; Lang, K. Samarium triiodide-catalyzed conjugate addition of indoles with electron-deficient olefins. *Tetrahedron Lett.* **2005**, *46*, 3859–3862. [CrossRef]

39. Firouzabadi, H.; Iranpoor, N.; Nowrouzi, F. The facile and efficient Michael addition of indoles and pyrrole to α,β-unsaturated electron-deficient compounds catalyzed by aluminium dodecyl sulfate trihydrate [Al(DS)$_3$]·3H$_2$O in water. *Chem. Commun.* **2005**, *6*, 789–791. [CrossRef] [PubMed]

40. More, G.V.; Bhanage, B.M. Synthesis of a chiral fluorescence active probe and its application as an efficient catalyst in the asymmetric Friedel–Crafts alkylation of indole derivatives with nitroalkenes. *Catal. Sci. Technol.* **2015**, *5*, 1514–1520. [CrossRef]

41. Guo, F.; Chang, D.; Lai, G.; Zhu, T.; Xiong, S.; Wang, S.; Wang, Z. Enantioselective and Regioselective Friedel–Crafts Alkylation of Pyrroles with Nitroalkenes Catalyzed by a Tridentate Schiff Base–Copper Complex. *Chem. Eur. J.* **2011**, *17*, 11127–11130. [CrossRef] [PubMed]

42. Hui, Y.; Lin, L.; Liu, X.; Feng, X. *Zinc Catalysis: Applications in Organic Synthesis*; Enthaler, S., Wu, X.-F., Eds.; WILEY-VCH Verlag: Weinheim, Germany, 2015.

43. Carmona, D.; Lamata, M.P.; Sánchez, A.; Viguri, F.; Oro, L.A. Enantioselective Friedel–Crafts alkylations catalysed by well-defined iridium and rhodium half-sandwich complexes. *Tetrahedron Asymmetry* **2011**, *22*, 893–906. [CrossRef]

44. Méndez, I.; Rodríguez, R.; Polo, V.; Passarelli, V.; Lahoz, F.J.; García-Orduña, P.; Carmona, D. Temperature Dual Enantioselective Control in a Rhodium-Catalyzed Michael-Type Friedel–Crafts Reaction: A Mechanistic Explanation. *Chem. Eur. J.* **2016**, *22*, 11064–11083. [CrossRef] [PubMed]

45. Dong, X.-W.; Liu, T.; Hu, Y.-Z.; Liu, X.-Y.; Che, C.-M. Urea postmodified in a metal–organic framework as a catalytically active hydrogen-bond-donating heterogeneous catalyst. *Chem. Commun.* **2013**, *49*, 7681–7683. [CrossRef] [PubMed]

46. McGuirk, C.M.; Katz, M.J.; Stern, C.L.; Sarjeant, A.A.; Hupp, J.T.; Farha, O.K.; Mirkin, C.A. Turning on catalysis: Incorporation of a hydrogen-bond-donating squaramide moiety into a Zr metal-organic framework. *J. Am. Chem. Soc.* **2015**, *137*, 919–925. [CrossRef] [PubMed]

47. Sobhani, S.; Jahanshahi, R. Nano *n*-propylsulfonated γ-Fe$_2$O$_3$ (NPS-γ-Fe$_2$O$_3$) as a magnetically recyclable heterogeneous catalyst for the efficient synthesis of 2-indolyl-1-nitroalkanes and bis(indolyl) methanes. *New J. Chem.* **2013**, *37*, 1009–1015. [CrossRef]

48. Jeganathan, M.; Kanagaraj, K.; Dhakshinamoorthy, A.; Pitchumani, K. Michael addition of indoles to β-nitrostyrenes catalyzed by HY zeolite under solvent-free conditions. *Tetrahedron Lett.* **2014**, *55*, 2061–2064. [CrossRef]

49. Lu, S.-F.; Du, D.-M.; Xu, J. Enantioselective Friedel−Crafts Alkylation of Indoles with Nitroalkenes Catalyzed by Bifunctional Tridentate Bis(oxazoline)−Zn(II) Complex. *Org. Lett.* **2006**, *8*, 2115–2118. [CrossRef] [PubMed]

50. Liu, H.; Du, D.-M. Development of Diphenylamine-Linked Bis(imidazoline) Ligands and Their Application in Asymmetric Friedel–Crafts Alkylation of Indole Derivatives with Nitroalkenes. *Adv. Synth. Catal.* **2010**, *352*, 1113–1118. [CrossRef]

51. Liu, H.; Xu, J.; Du, D.M. Asymmetric Friedel-Crafts alkylation of methoxyfuran with nitroalkenes catalyzed by diphenylamine-tethered bis(oxazoline)-Zn(II) complexes. *Org. Lett.* **2007**, *9*, 4725–4728. [CrossRef] [PubMed]

52. Liu, H.; Lu, S.F.; Xu, J.; Du, D.M. Asymmetric Friedel–Crafts Alkylation of Electron-Rich *N*-Heterocycles with Nitroalkenes Catalyzed by Diphenylamine-Tethered Bis(oxazoline) and Bis(thiazoline) ZnII Complexes. *Chem. Asian J.* **2008**, *3*, 1111–1121. [CrossRef] [PubMed]

53. Liu, H.; Du, D.-M.M. Immobilization of Diphenylamine-Linked Bis(oxazoline) Ligands and Their Application in the Asymmetric Friedel–Crafts Alkylation of Indole Derivatives with Nitroalkenes. *Eur. J. Org. Chem.* **2010**, *2010*, 2121–2131. [CrossRef]

54. Handa, S.; Gnanadesikan, V.; Matsunaga, S.; Shibasaki, M. *syn*-Selective Catalytic Asymmetric Nitro-Mannich Reactions Using a Heterobimetallic Cu−Sm−Schiff Base Complex. *J. Am. Chem. Soc.* **2007**, *129*, 4900–4901. [CrossRef] [PubMed]

55. Maayan, G.; Christou, G. 'Old' Clusters with New Function: Oxidation Catalysis by High Oxidation State Manganese and Cerium/Manganese Clusters Using O$_2$ Gas. *Inorg. Chem.* **2011**, *50*, 7015–7021. [CrossRef] [PubMed]

56. Evangelisti, F.; More, R.; Hodel, F.; Luber, S.; Patzke, G.R. **3d**–**4f** {Co$^{II}_3$Ln(OR)$_4$} Cubanes as Bio-Inspired Water Oxidation Catalysts. *J. Am. Chem. Soc.* **2015**, *137*, 11076–11084. [CrossRef] [PubMed]

57. Griffiths, K.; Gallop, C.W.D.; Abdul-Sada, A.; Vargas, A.; Navarro, O.; Kostakis, G.E. Heteronuclear **3d**/DyIII coordination clusters as catalysts in a domino reaction. *Chem. Eur. J.* **2015**, *21*, 6358–6361. [CrossRef] [PubMed]

58. Griffiths, K.; Kumar, P.; Mattock, J.D.; Abdul-Sada, A.; Pitak, M.B.; Coles, S.J.; Navarro, O.; Vargas, A.; Kostakis, G.E. Efficient Ni$^{II}_2$Ln$^{III}_2$ Electrocyclization Catalysts for the Synthesis of *trans*-4,5-Diaminocyclopent-2-enones from 2-Furaldehyde and Primary or Secondary Amines. *Inorg. Chem.* **2016**, *55*, 6988–6994. [CrossRef] [PubMed]

59. Griffiths, K.; Kumar, P.; Akien, G.; Chilton, N.F.; Abdul-Sada, A.; Tizzard, G.J.; Coles, S.; Kostakis, G.E. Tetranuclear Zn/**4f** coordination clusters as highly efficient catalysts for Friedel–Crafts alkylation. *Chem. Commun.* **2016**, *52*, 7866–7869. [CrossRef] [PubMed]

60. Griffiths, K.; Dokorou, V.N.; Spencer, J.; Abdul-Sada, A.; Vargas, A.; Kostakis, G.E. Isoskeletal Schiff base polynuclear coordination clusters: Synthetic and theoretical aspects. *CrystEngComm* **2016**, *18*, 704–713. [CrossRef]

61. 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]

62. Palatinus, L.; Chapuis, G. *SUPERFLIP*—A computer program for the solution of crystal structures by charge flipping in arbitrary dimensions. *J. Appl. Crystallogr.* **2007**, *40*, 786–790. [CrossRef]

63. Sheldrick, G.M. Acta Crystallogr. Crystal structure refinement with *SHELXL. Sect. C Struct. Chem.* **2015**, *71*, 3–8. [CrossRef] [PubMed]

64. Macrae, C.F.; Edgington, P.R.; McCabe, P.; Pidcock, E.; Shields, G.P.; Taylor, R.; Towler, M.; Van De Streek, J. Mercury: Visualization and analysis of crystal structures. *J. Appl. Crystallogr.* **2006**, *39*, 453–457. [CrossRef]