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Assembly of chiral monodentate ligands to chelates by donor–acceptor interactions

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Abstract—The first examples of assembling monodentate oxazoline donor and acceptor ligands by charge transfer interactions are described to mimic bidentate ligands in asymmetric catalysis. The corresponding copper(II) complexes were used in an enantioselective Diels–Alder reaction and showed very high efficiency, but only moderate stereoselectivity. These complexes were successfully recovered and reused after precipitation in pentane.

1. Introduction

Asymmetric catalysis is nowadays a subject of great concern for the preparation of enantioenriched valuable synthons in an economic and environmentally friendly way. The efficient transfer of the chirality from an optically active catalyst to the reaction product is a transformation that perfectly meets the concept of atom economy, one of the fundaments of the twelve principles of green chemistry.[1] Highly valuable catalysts, in terms of activity and enantioselectivity, are often designed from bidentate ligands and numerous efforts have thus been devoted towards the fine tuning of synthetic methodologies for their easy preparation. Although combinatorial procedures have been developed, the facile access to numerous, structurally different bidentate ligands is not obvious. An alternative strategy consists of the preparation of targeted monodentate ligands that can then be assembled around the metal to form chelates, thanks to additional non-covalent interactions. According to the reversibility of this additional link, a great diversity of new two-point coordinating ligands is available for the search of efficient chiral catalysts active in various asymmetric transformations. Some research has already been performed to prove the success of this strategy for homogeneous catalysis and has recently been reviewed.[2] For example, they involve the preferential formation of heterodimeric catalysts from two monodentate ligands, probably favoured by weak interactions, such as van der Waals, π-stacking or dipole–dipole interactions. This was simultaneously reported by Reetz et al.[3] and Feringa and Minnaard.[4] Stronger interactions, such as hydrogen bonding, were also studied by Breit et al. who modified monodentate ligands by structural complementary motifs to mimic the adenine–thymine base pair in DNA[5] or prepared various chelates by interactions based on the 2-pyridone/hydroxypyridine tautomeric system.[6] The urea motif, and its complementary hydrogen bonds, was exploited by Reek et al. for the supramolecular assembly of Binol-based phosphite ligands.[7] Coordinative interactions were also studied for the assembly of monodentate ligands in a heterodimeric way; Reek et al. studied the ability of zinc(II) porphyrins to form stable complexes with pyridine derivatives as nitrogen donors. They thus prepared various phosphite zinc(II) porphyrins and monodentate phosphorous ligands bearing a nitrogen donor group.[8] Metal-directed self-assembly based on the rapid formation of bis(oxazoline) Zn complex has also been reported by Takacs et al. in which other coordinating groups are suitably disposed to bind a second metal, useful for the catalysis.[9] Recently, Ishihara et al. synthesized and characterized self-assembled macrocyclic Pd(II) and Cu(II) complexes through *trans*-chelation with new *P*,*N*- or bis(oxazoline) ligands.[10] Most of these chelates associated by non-covalent interactions involved phosphorous-containing ligands. They were mainly tested in the presence of rhodium pre-catalysts for the efficient asymmetric hydrogenation of various substrates or with palladium complexes for successful nucleophilic allylic substitutions.

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We have recently described the efficient recovery of chiral copper–bis(oxazoline) complexes by the formation of reversible non-covalent donor–acceptor interactions, between anthracene-modified ligands and additional trinitrofluorenone.[11] We herein report as preliminary results, the first example, to the best of our knowledge, concerning the possibility of assembling monodentate oxazoline ligands by charge transfer interactions to mimic bidentate ligands for asymmetric catalysis. A schematic representation for this concept is given below (Fig. 1).

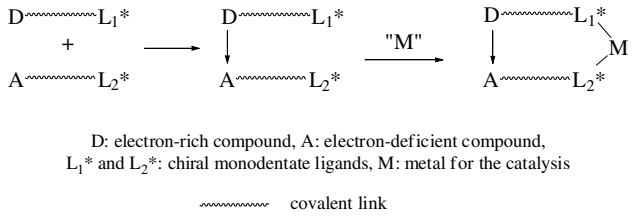


Figure 1. Formation of asymmetric catalysts from chelates assembled by reversible charge transfer interactions.

The synthesis of various mono(oxazolines) possessing either an electron-rich motif (an anthracene group) or an electron-deficient substituent (based on the 2,4,7-trinitrofluoren-9-one backbone) is described; these new ligands are fully characterized. In the presence of copper(II) triflate as precatalyst, different ligand combinations were tested in the asymmetric Diels–Alder reaction between cyclopentadiene and 3-but-2-enoyl-oxazolidin-2-one. Using this procedure, non-symmetric bis-(oxazolines) type ligands were easily generated and afforded various new chiral environments around the coordinating metal, by assembling different monodentate oxazoline ligands. The direct synthesis of non-symmetrical bis(oxazolines) is not straightforward with only few examples reported in the literature.[12] Moreover, these new assembled copper complexes were easily recovered by precipitation in pentane and directly recycled in a new catalytic transformation.

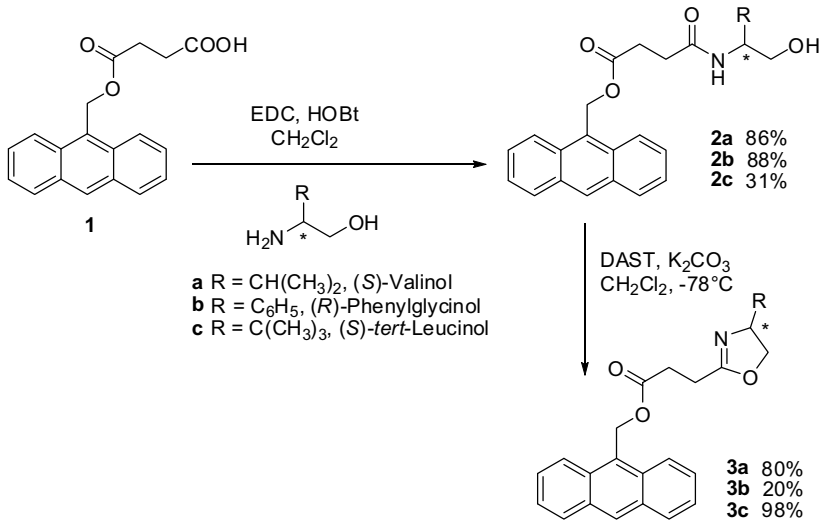
2. Results and discussion

2.1. Synthesis

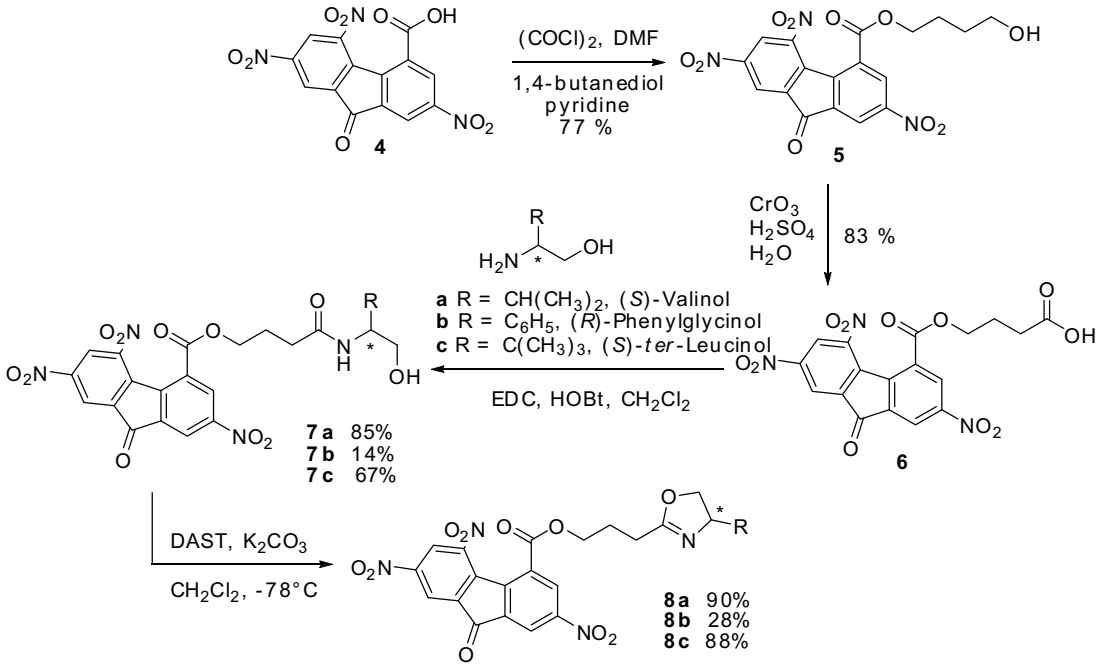
Both types of substituted mono(oxazolines) were synthesized following the same strategy, that is, the formation of the oxazoline moiety from a carboxylic acid functional group via the synthesis of various amides according to the targeted amino alcohols. The final step involved the ring closure to the heterocycle by diethylaminosulfur trifluoride-induced activation.[13] We were successful in preparing derivatives from (*S*)-valinol, (*R*)-phenyglycinol and (*S*)-*tert*-leucinol; however all attempts to cyclize (1*R*,2*S*)-1-amino-2-indanol compounds with this procedure failed. The modification of the coordinating oxazoline group by either a donor or an acceptor motif was considered from commercially or easily available substituted anthracene or nitrofluorenone derivatives. In both cases, flexible link with a similar length was installed between the functional groups suitable for either the formation of the active chiral organometallic species or the preparation of the charge transfer complex for the reversible self-assembly. The synthesis of the donor derivatives is depicted in Scheme 1.

The amidation reaction of 4-(9-anthrylmethoxy)-4-oxobutanoic acid **1**[14] was performed in the presence of three different aminoalcohols. The coupling was activated with *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide (EDC)[15] and 1-hydroxybenzotriazole hydrate (HOBt) providing the targeted amide derivatives in moderate to good yields that were not further optimized. The final cyclization into the oxazoline ligands **3a**–**c** was realized with fluoride activation and allowed the isolation of three donor ligands that were fully characterized.

A similar procedure (see Scheme 2) was followed for the synthesis of the corresponding acceptor ligands starting from 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylic acid **4**.[16] The spacer was settled via the reaction with 1,4-butanediol to provide alcohol **5** in good yield. Subsequent oxida-



Scheme 1. Synthesis of anthracene-modified mono(oxazolines).



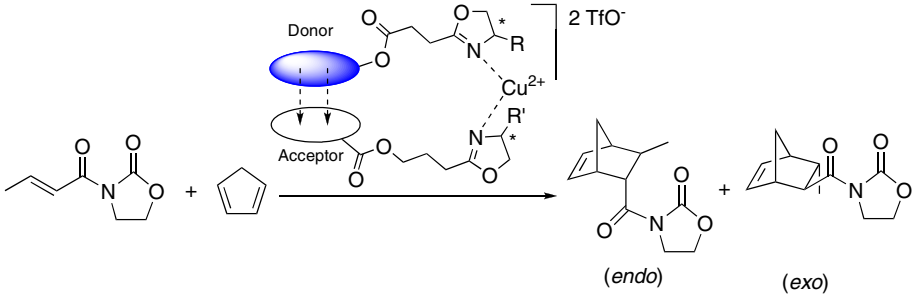
Scheme 2. Synthesis of trinitrofluorenone-modified mono(oxazolines).

tion of the hydroxyl group by the Jones procedure furnished the carboxylic acid **6** in 83% yield. The synthesis of the acceptor ligands was identical to that described in Scheme 1 for the preparation of the donor counterparts, and the targeted compounds **8a**–**c** were thus isolated in moderate to high unoptimized yields.

2.2. Catalytic tests

Chiral bis(oxazoline) ligands are valuable chelates for asymmetric catalysis involving a large variety of metals, for the use of the corresponding complexes in numerous enantioselective transformations.[17] We have decided to test our charge-transfer assembled chelates in the bis(oxazoline)–copper catalyzed Diels–Alder reaction developed by Evans et al.[18] This transformation uses the catalytic system derived from 2,2′-isopropylidenebis[(4*S*)-4-*tert*-butyl-2-oxazoline] and copper (II) and allows the simultaneous formation of two new carbon–carbon bonds in a highly diastereo- and enantioselective fashion (see Scheme 3).[19] Under optimized conditions (in dichloromethane at −15 °C), the *endo* compound was prepared as the major isomer (*endo*/*exo* = 96/4) with a high enantioselectivity (97% ee). This transformation was thus chosen as a test reaction to confirm our concept. Ligands arising from (*S*)-valinol **3a** and **8a** were first selected for the preparation of a copper complex.

The experimental procedure involves mixing the ligands in dichloromethane before their addition to $Cu(OTf)_2$ (each compound in an equimolar quantity). The resulting solution is stirred for at least 3 h before the addition of the reactants. The formation of the complex is accompanied with the appearance of a red colour (which is characteristic of the charge transfer) although the reaction mixture remains homogeneous. Results obtained with the valinol ligands are reported in Table 1. The first catalytic test was attempted at −15 °C, and after 15 h reaction time, the expected mixture of *endo*/*exo* products could be isolated albeit in a quite low yield (entry 1). These results nevertheless confirm that an active species for the Diels–Alder reaction can be obtained from monodentate ligands and copper(II) triflate. The enantiomeric excesses could be determined for each diastereoisomer by chiral HPLC analysis indicating, however, a



Scheme 3. Diels–Alder reaction for the evaluation of the new chiral copper complexes.

Table 1. Catalytic tests with valinol-type ligands

Entry[a]	Ligand	T (°C)	Conv[b] (%)	Yield[c] (%)	*endo*/*exo*[d]	*endo* ee[e] (%) (config)	*exo* ee[e] (%) (config)
1 1st run	**3a/8a**	−15	25	20	76/24	8 (2*S*)	15 (2*S*)
2 2nd run	**3a/8a**	25	50	35	77/23	<5	5 (2*S*)

[a] Conditions: $Cu(OTf)_2$ 12 mol % (0.036 mmol), each ligand 10 mol % (0.033 mmol) in 500 μL anhydrous CH_2Cl_2, oxazolidinone (0.33 mmol) in 250 μL anhydrous CH_2Cl_2, cyclopentadiene (2.4 mmol, 200 μL), 15 h.
[b] Determined by ^1H NMR spectroscopy.
[c] Isolated yield.
[d] Diastereoselectivity was determined by ^1H NMR spectroscopy.
[e] Enantioselectivity was determined by chiral HPLC analysis, absolute configuration was assigned by comparison (see Ref. 21 and Section 4).

low enantioselectivity for both compounds. Interestingly, the catalytic species could be recovered by the addition of pentane that led to the precipitation of a red powder. Subsequent washing with pentane and the addition of new reagents (Table 1, entry 2) allowed the reuse of the catalyst at room temperature, as an attempt to improve the yield, affording the products in a moderate yield but with diminished enantioselectivities. In our hands, the more usual 2,2′-isopropylidenebis[(4*S*)-4-isopropyl-2-oxazoline] associated to copper(II) triflate promoted the reaction between 3-(but-2-enoyl)oxazolidin-2-one and cyclopentadiene at 0 °C in dichloromethane, and the expected *endo* major product was obtained with an enantioselectivity of 40%.[11b,20] The targeted self-assembled bidentate ligand arising from CTC interactions between **3a** and **8a** thus afforded a moderately active catalytic species in the presence of copper, a precatalyst for the Diels–Alder reaction, but a significant loss in enantioselectivity was unfortunately observed compared to the parent methylene-bridge bis(oxazoline).

Similar experiments were performed in the presence of ligands **3b** and **8b** arising from (*R*)-phenylglycinol (see Table 2). Some preliminary tests showed that an active species was only obtained if the complex was prepared in the presence of an excess of copper(II) triflate compared to the oxazoline ligands. Even if this phenomenon remained unclear, we propose that undesired complexation of copper to the anthracene/trinitrofluorenone link may occur, leading to less active complexes in the subsequent catalysis experiments.[22] It was verified that no reaction occurred in the absence of any ligand. A catalytic test was thus run in the presence of **3b** as a unique ligand and copper triflate in excess, leading to the formation of a homodimeric complex (Table 2, entry 1). The resulting catalyst proved to be much more efficient than that derived from the valinol ligands since an almost complete conversion of the substrates was obtained in 15 h at −15 °C leading to the isolated products in 85% yield. The *endo* product was obtained as the major compound with 66% de and 28% ee in favour of the major (2*R*) enantiomer. The *exo* compound was isolated with 22% ee. Accordingly, trinitrofluorenone-substituted monooxazoline ligand **8b** was tested as ligand under the same conditions (Table 2, entries 2–4). This new homodimeric catalyst was again efficient for the formation of the *endo* product with 62% de albeit in a nearly racemic form. The enantioselectivity of the minor *exo* product was interestingly enhanced up to 39%. This catalyst was successfully reused twice more without showing any loss in activity (even at −40 °C) but a slight decrease in enantioselectivity at each recycling. The 1:1 mixture of compounds **3b** and **8b** in the presence of copper(II) triflate also led to an efficient Diels–Alder catalyst that could be very efficiently recycled three times (Table 2, entries 5–8). This ligand mixture may lead to the formation of two homodimeric copper complexes (with two donor or two acceptor ligands) and one heterodimeric complex, resulting from the charge transfer complex. The results in terms of diastereoselectivity are analogous to those obtained in the presence of the homodimeric complexes from either **8b** or **3b**, but the *exo* product showed only 20% ee. While the *endo* product was obtained in all cases with a low enantioselectivity, it is worthwhile mentioning that a reversal in the major enantiomer is observed

Table 2. Catalytic tests with phenylglycinol-type ligands

Entry[a]	Ligand	T (°C)	Conv[b] (%)	Yield[c] (%)	*endo*/*exo*[d]	*endo* ee[e](%) (config)	*exo* ee[e] (config)
1 1st run	**3b**	−15	96	85	83/17	28 (2*R*)	22 (2*R*)
2 1st run	**8b**	−15	100	90	81/19	7 (2*S*)	39 (2*R*)
3 2nd run	**8b**	−15	100	90	83/17	7 (2*S*)	29 (2*R*)
4 3rd run	**8b**	−40	100	90	87/13	6 (2*S*)	21 (2*R*)
5 1st run	**3b/8b**[f]	−15	100	85	83/17	8 (2*R*)	20 (2*R*)
6 2nd run	**3b/8b**[f]	−15	100	90	83/17	8 (2*R*)	20 (2*R*)
7 3rd run	**3b/8b**[f]	−15	100	90	85/15	7 (2*R*)	19 (2*R*)
8 4th run	**3b/8b**[f]	−40	60	55	86/14	<5	16 (2*R*)

[a] Conditions: $Cu(OTf)_2$ 10 mol % (0.033 mmol), ligand 6 mol % (0.020 mmol) in 500 μL anhydrous CH_2Cl_2, oxazolidinone (0.33 mmol) in 250 μL anhydrous CH_2Cl_2, cyclopentadiene (2.4 mmol, 200 μL), 15 h.
[b] Determined by ^1H NMR spectroscopy.
[c] Isolated yield.
[d] Diastereoselectivity determined by ^1H NMR spectroscopy.
[e] Enantioselectivity determined by chiral HPLC analysis, absolute configuration was assigned by comparison (see Ref. 21 and Section 4).
[f] 6 mol % of each ligand.

using only ligand **3b** or the corresponding acceptor **8b**. The major (2*R*)-*endo*-compound is also obtained in the presence of the mixture of both ligands, suggesting that different catalytic species are involved in those experiments.

Further experiments could be conducted with the *tert*-leucinol derived ligands. The parent bridge bis(oxazoline) ligand is indeed the most efficient chelate for copper to promote this transformation.[18] In this case again, the formation of the organometallic species proved to be more challenging and reproducible results could only be obtained by working with a higher catalyst loading in the presence of molecular sieves. The donor ligand **3c** allowed the formation of an active and diastereoselective catalyst that led to the formation of the major *endo*-compound in 42% ee (Table 3, entry 1). This catalyst, however, was demonstrated to be less stable than the other previously described since its recycling (albeit run at −65 °C) was accompanied with an important loss of activity and enantioselectivity. The corresponding acceptor ligand **8c** was also engaged alone in the catalytic transformation and led interestingly to the isolation of both compounds with a similar diastereoisomeric ratio but the *endo* product was nearly racemic, whereas the minor *exo* compound was prepared with high enantiomeric excess (up to 73%), the highest value obtained in this study (Table 3, entries 3 and 4).

Mixing both ligands in the presence of 25 mol % copper triflate also led to the preparation of an active catalyst that could be successfully reused. The results in terms of enantioselectivity indicated that probably several species were present in solution since both compounds were recovered with different enantiomeric excesses: the *endo* product with 19% ee and the *exo* compound with 46% ee. The lowering of the temperature (Table 3, entry 7) improved the enantiomeric excess of the *endo* diastereoisomer (up to 36%) but had no influence on the *exo* product. It can be concluded that the homodimeric complexes formed from the donor or the acceptor ligands gave the best enantioselectivities, either on the *endo* or on the *exo* compound, respectively. When both ligands are present, it is difficult to conclude on the structure of the active species. From a descriptive point of view, it should be noted that the colour of the reaction mixture varies markedly depending on the species present in solution. When two donor ligands (of the **3** series) are reacting with copper triflate, the resulting solution becomes brown-yellow but turns to dark purple when two electron-deficient compounds (series **8**) are involved. Mixing both types of ligands led to a typically different brown-red solution. One can thus not exclude that in this case, the heterodimeric complex exists thanks to the donor–acceptor interactions. The resulting catalyst seems, however, less selective.

Finally, some catalytic tests were attempted in the presence of a mixture of ligands, as donor–acceptor chelates possessing non-symmetric oxazoline moieties. A first experiment implied the use of the donor ligand with the *tert*-leucinol oxazoline **3c** and the acceptor one substituted by a valinol-type derivative **8a**. In the presence of equimolar quantities of copper, the resulting catalyst proved to be poorly active (Table 4, entry 1) and led mainly to the *endo* product with an (*S*)-configuration and 16% ee. The reuse of this catalytic species was preceded with the addition of 10 mol % more $Cu(OTf)_2$ thus leading in the second run to a more active complex that also afforded the minor *exo* product with 16% ee (Table 4, entry 2).

Mixing ligand **3b** and acceptor **8c** also afforded an active catalyst that led to the formation of the *endo* product with 13% ee in the (2*R*)-configuration, and the *exo* product was prepared with 38% ee. From all these results, it seems that, albeit they probably possess different structures, all the prepared complexes are active catalysts for the preparation of the expected products at various temperatures with very similar diastereoselectivities. The enantiofacial differentiation is, however, much more sensitive to these structural variations since the homodimeric complexes arising from the acceptor series markedly favour the enantioselectivity of the minor *exo* isomer (see Table 2, entries 2–4 and Table 3, entries 3 and 4). Contrarily, the homodimeric complexes prepared with the donor ligands **3b** and **3c** (Table 2 entry 1 and Table 3, entries 1 and 2) afforded the major *endo* compound with a higher enantioselectivity. From Table 4—entry 3, it is interesting to note that the configuration of the major enantiomer of the *endo* product (2*R*) is probably driven by ligand **3b**, while the enantioselectivity of the *exo* counterpart by ligand **8c** (2*S*), is in complete accordance with the above-mentioned observations.

Table 3. Catalytic tests with *tert*-leucinol-type ligands

Entry[a]	Ligand	*T* (°C)	Conv[b] (%)	Yield[c] (%)	*endo*/*exo*[d]	*endo* ee[e] (%) (config)	*exo* ee[e] (%) (config)
1 1st run	**3c**	−15	100	90	84/16	42 (2*S*)	<5
2 2nd run	**3c**	−65	24	20	88/12	28 (2*S*)	<5
3 1st run	**8c**	−15	68	60	86/24	<5	70 (2*S*)
4 2nd run	**8c**	−65	48	40	79/21	<5	73 (2*S*)
5 1st run	**3c/8c**[f]	−15	100	90	81/19	19 (2*S*)	46 (2*S*)
6 2nd run	**3c/8c**[f]	−15	100	90	83/17	19 (2*S*)	46 (2*S*)
7 1st run	**3c/8c**[f]	−65	60	55	87/13	36 (2*S*)	47 (2*S*)

[a] Conditions: $Cu(OTf)_2$ 25 mol % (0.082 mmol), ligand 22 mol % (0.072 mmol) in 500 μL anhydrous CH_2Cl_2, oxazolidinone (0.33 mmol) in 250 μL anhydrous CH_2Cl_2, cyclopentadiene (2.4 mmol, 200 μL), 15 h, molecular sieves.
[b] Determined by ^1H NMR spectroscopy.
[c] Isolated yield.
[d] Diastereoselectivity determined by ^1H NMR spectroscopy.
[e] Enantioselectivity determined by chiral HPLC analysis, absolute configuration was assigned by comparison (see Ref. 21 and Section 4).
[f] 11 mol % of each ligand.

Table 4. Catalytic tests with mixed ligands

Entry[a]	Ligand	T (°C)	Conv[b] (%)	Yield[c] (%)	*endo*/*exo*[d]	*endo* ee[e] (%) (config)	*exo* ee[e] (%) (config)
1 1st run	**3c/8a**	−15	40	35	83/17	16 (2*S*)	<5
2 2nd run	**3c/8a**[f]	−15	100	90	80/20	16 (2*S*)	16 (2*S*)
3 1st run	**3b/8c**	−15	100	90	80/20	13 (2*R*)	38 (2*S*)

[a] Conditions: $Cu(OTf)_2$ 25 mol % (0.082 mmol), each ligand 11 mol % (0.036 mmol) in 500 μL anhydrous CH_2Cl_2, oxazolidinone (0.33 mmol) in 250 μL anhydrous CH_2Cl_2, cyclopentadiene (2.4 mmol, 200 μL), 15 h, molecular sieves.
[b] Determined by ^1H NMR spectroscopy.
[c] Isolated yield.
[d] Diastereoselectivity determined by ^1H NMR spectroscopy.
[e] Enantioselectivity determined by chiral HPLC analysis, absolute configuration was assigned by comparison (see Ref. 21 and Section 4).
[f] 10 mol % $Cu(OTf)_2$ are added.

3. Conclusion

In conclusion, we have reported the synthesis of new mono(oxazoline) ligands from three different amino alcohols and bearing either an electron-rich anthracene group or an electron-poor trinitrofluorenone substituent. In the presence of copper triflate as a pre-catalyst, all ligand combinations that were tested proved to lead to active and enantioselective catalysts in the Diels–Alder reaction between cyclopentadiene and 3-but-2-enoyl-oxazolidin-2-one. When using only one mono(oxazoline) ligand in the catalysis,[23] the best results were obtained in terms of enantioselectivity for either the *endo* or the *exo* product, according to the presence of the anthracene or trinitrofluorenone group. In those cases, it can be proposed that the interactions of type π-stacking are involved for favouring the formation of bidentate homodimeric complexes as efficient catalysts in asymmetric catalysis. Mixing one electron-deficient and one electron-rich ligand also afforded active Diels–Alder catalysts as the first examples of bidentate ligands assembled by charge-transfer interactions. As a weak assembling is, however, involved, the formation of the heterodimeric complex is probably not largely favoured and a mixture of different species, as equilibria in solution, is present leading to lower enantioselectivities for the expected products. For favouring the privileged formation of the heterodimeric complex, the structure of the targeted ligands will be modified towards a more rigid and/or shorter link between the donor–acceptor centre and the catalytic site. These assemblies by charge-transfer interactions furthermore allow the easy preparation of new catalysts bearing oxazoline groups that are not symmetrical. The synthesis of corresponding bis(oxazolines) from different amino-alcohols is indeed not straightforward,[12] but some of them were already particularly active in targeted transformations. Guiry et al. reported the efficient use of non-symmetric bis(oxazoline) ligands in the asymmetric methallylation of various aldehydes.[12d] We aim to test our new catalytic systems in such a type of transformations. Finally, we have shown that our catalysts can be easily recovered by precipitation through pentane addition and could be reused several times with no loss in their efficiency. Work is currently in progress in our laboratory to improve the ligand structures and to optimize the charge transfer interactions for favouring the formation of heterodimer combinations with both enhanced activities and enantioselectivities.

4. Experimental

4.1. General

All reactions were carried out under argon in oven-dried glassware with magnetic stirring. Solvents were distilled before use from calcium hydride. Cyclopentadiene was distilled by cracking dicyclopentadiene over calcium hydride. ^1H NMR spectra were recorded on a BRUKER AM 250 (250 MHz), AM 300 (300 MHz) or AM 360 (360 MHz) as $CDCl_3$ solutions, and data are reported in ppm relative to the solvent (7.27 ppm). ^{13}C NMR spectra were recorded on a BRUKER AM 250 (62.5 MHz) as $CDCl_3$ solutions and data are reported in ppm relative to the solvent (77.0 ppm). Optical rotations were measured as solutions in 10 cm cells using a PERKIN ELMER 241 polarimeter. Melting points were measured with a Reichert instrument. Mass spectra were recorded on a Finnigan MAT 95 S spectrometer. HPLC analyses were carried out on a PERKIN–ELMER chromatograph equipped with a diode array UV detector using an IA or a WHELK column. IR spectra were recorded as KBr disks using a PERKIN–ELMER spectrometer. Elemental analyses were performed by the C.N.R.S. Service of Microanalyses in Gif-sur-Yvette (France). 4-(9-Anthrylmethoxy)-4-oxobutanoic acid **1** was prepared according to Ref. 14. 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylic acid **4** was synthesized from 9-oxo-9*H*-fluorene-4-carboxylic acid[24] following the procedure described in Ref. 16. (*E*)-3-but-2-enoyloxazolidin-2-one was prepared according to the procedure described in Ref. 11.

4.1.1. 2,5,7-Trinitro-9-oxo-9*H*-fluorene-4-carboxylic acid 4-hydroxy-butyl ester 5. In an oven-dried flask and under an argon atmosphere, 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylic acid (5.00 g, 13.9 mmol, 1.0 equiv) was dissolved in 30 mL CH_2Cl_2. Oxalyl chloride (3.6 mL, 41.7 mmol, 3.0 equiv) was added at room temperature followed by 3 drops of DMF. The mixture was stirred for 1 h at room temperature until effervescence stopped, and then oxalyl chloride in excess was removed under reduced pressure. In a 50 mL flask under argon, butane-1,4-diol (11.6 mL, 130.9 mmol, 10.0 equiv), pyridine (2.4 mL, 29.4 mmol, 2.1 equiv) were dissolved in anhydrous dichloromethane (5 mL). This solution was transferred under argon to the freshly prepared acylchloride and further stirred overnight at room temperature. The solution was hydrolyzed with an

aqueous solution of HCl 1 N (20 mL). The aqueous layer was extracted with CH_2Cl_2 (2 × 20 mL), and the combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuum. The residue was purified by chromatography on silica gel (CH_2Cl_2/AcOEt, 90/10) to afford product **5** as a yellow solid (4.6 g, 77% yield).

$C_{18}H_{13}N_3O_{10}$ (431.31). Yellow powder. Mp = 173–175 °C. R_f (in CH_2Cl_2/MeOH, 98/2) = 0.80. ^{1}H NMR (300 MHz, in $CDCl_3$): δ 1.67 (1H, s); 1.68–1.77 (2H, m); 1.92–1.97 (2H, m); 3.76 (2H, t, ^3J = 6.4 Hz); 4.44 (2H, t, ^3J = 6.4 Hz); 8.76–8.95 (4H, m). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 25.6; 28.3; 61.9; 64.3; 113.9; 123.0; 125.9; 126.9; 127.8; 129.6; 133.1; 134.1; 134.2; 134.8; 135.6; 147.0; 169.1; 182.1. MS (ESI−) *m*/*z*: 431.0 [M−1] (100%). Anal. Calcd for $C_{18}H_{13}N_3O_{10}$ C, 50.12; H, 3.04; N, 9.74, O 37.09. Found: C, 50.17; H, 2.98; N, 9.47. IR (KBr): *v* 1050; 1089; 1159; 1232; 1342; 1466; 1542; 1594; 1617; 1738; 2874; 3091; 3300.

4.1.2. 2,5,7-Trinitro-9-oxo-9*H*-fluorene-4-carboxylic acid 3-carboxy-propyl ester 6. A solution of sulfuric acid (0.8 mL, 14.0 mmol, 1.5 equiv), CrO_3 (1.86 g, 18.6 mmol, 2.0 equiv) and water (2.7 mL, 149.0 mmol, 16.0 equiv) was added slowly to a solution of **5** (4.02 g, 9.3 mmol, 1.0 equiv) in acetone (16 mL). The black mixture was stirred for 40 min at room temperature, and then diluted with Et_2O (20 mL) and water (20 mL). The aqueous layer was extracted with CH_2Cl_2 (2 × 20 mL), and the combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuum. The residue was precipitated in a Et_2O/CH_2Cl_2 (9/1) mixture, filtered, washed with Et_2O, and dried in vacuum to afford a yellow powder (3.44 g, 83% yield).

$C_{18}H_{11}N_3O_{11}$ (445.29). Yellow powder. Mp = 176 °C. R_f (in CH_2Cl_2/AcOEt, 90/10) = 0.80. ^{1}H NMR (300 MHz in $CDCl_3$): δ 2.13–2.23 (2H, m); 2.58 (2H, t; ^3J = 7.0 Hz); 4.30–4.60 (2H, m); 8.75–8.84 (4H, m). ^{13}C NMR (62.5 MHz in $CDCl_3$): 26.4; 30.9; 64.6; 114.1; 123.0; 126.1; 126.9; 127.8; 129.6; 133.1; 134.1; 134.4; 134.8; 135.6; 147.0; 169.1; 179.7; 182.1. MS (ESI−) *m*/*z*: 370.0 (100%); 444.0 [M−1] (46%). HRMS (ESI−) *m*/*z* calcd for $C_{18}H_{10}N_3O_{11}$: 444.031, found: 444.031. IR (KBr): *v* 1088; 1180; 1233; 1315; 1345; 1451; 1537; 1593; 1614; 1713; 1742; 2880; 3090; 3567; 3819.

4.1.3. β-Hydroxy-amides: general procedure. In a 100 mL flask under argon, acid **1** or **6** (7.7 mmol, 1.0 equiv), and HOBt (1.20 g, 8.5 mmol, 1.1 equiv) were dissolved in CH_2Cl_2 (70 mL). Next, EDC (1.5 mL, 8.5 mmol, 1.1 equiv) dissolved in CH_2Cl_2 (10 mL) was added at 0 °C and the mixture was stirred for 1 h. The amino alcohol (9.2 mmol, 1.2 equiv) in CH_2Cl_2 (15 mL) was added dropwise, and the solution was stirred overnight at room temperature. The solution was quenched with an aqueous HCl 3 M solution (20 mL). The aqueous layer was extracted with CH_2Cl_2 (2 × 20 mL), and the combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuum. The residue was purified by chromatography on silica gel (CH_2Cl_2/AcOEt, 20/80, 1% Et_3N, then AcOEt 100%, 1% Et_3N) to afford the desired product.

4.1.4. (Anthracen-10-yl)methyl 3-((*S*)-1-hydroxy-3-methylbutan-2-ylcarbamoyl)propanoate 2a. $C_{24}H_{27}NO_4$ (393.48). 86% yield. Beige powder. Mp = 179–180 °C. R_f (in AcOEt/cyclohexane, 70/30) = 0.09. ^{1}H NMR (300 MHz in $CDCl_3$): δ 0.88 (3H, d, ^3J = 6.8 Hz); 0.91 (3H, d, ^3J = 6.8 Hz); 1.70–1.90 (1H, m); 2.40–2.75 (4H, m); 3.50–3.65 (3H, m); 5.74 (1H, d, ^3J = 7.2 Hz); 6.14 and 6.20 (2H, 2d, ^3J = 12,5 Hz); 7.50–8.02 (4H, m); 8.03 (2H, d, ^3J = 8.3 Hz); 8.32 (2H, d, ^3J = 8.3 Hz); 8.50 (1H, s). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 18.7; 19.3; 28.9; 29.7; 31.2; 57.1; 59.2; 63.5; 123.8; 125.1; 125.9; 126.7; 129.0; 129.2; 130.9; 131.3; 172.3; 173.3. MS (ESI+) *m*/*z*: 416 [M+Na$^+$] (100%). HRMS (ESI+) *m*/*z* calcd for $C_{24}H_{27}NO_4Na$: 416.1832, found: 416.1846. IR (KBr): *v* 1063; 1169; 1385; 1434; 1559; 1639; 1725; 2870; 2929; 3087; 3293.

4.1.5. 3-((*S*)-1-Hydroxy-3-methylbutan-2-ylcarbamoyl)-propyl 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylate 7a. $C_{23}H_{22}N_4O_{11}$ (530.44). 85% yield. Brown powder. Mp = 83 °C. R_f (in AcOEt/cyclohexane, 70/30) = 0.81. ^{1}H NMR (250 MHz in $CDCl_3$): δ 0.94 (3H, d, ^3J = 4.7 Hz); 0.97 (3H, d, ^3J = 4.7 Hz); 1.85–1.93 (1H, m); 2.17–2.25 (2H, m); 2.46 (2H, t, ^3J = 7.0 Hz); 3.60–3.80 (3H, m); 4.40–4.50 (2H, m); 5.78 (1H, d, ^3J = 7.3 Hz); 8.77 (1H, d, ^4J = 2.2 Hz); 8.84 (1H, d, ^4J = 1.9 Hz); 8.87 (1H, d, ^4J = 2.4 Hz); 8.95 (1H, d, ^4J = 1.9 Hz). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 18.9; 19.5; 24.7; 29.0; 32.8; 57.2; 63.9; 66.8; 121.9; 122.6; 125.3; 130.6; 132.2; 137.8; 138.9; 139.8; 143.6; 146.6; 149.4; 149.7; 164.5; 172.6; 184.9. MS (ESI+) *m*/*z* = 553.3 [M+Na$^+$] (100%). HRMS (ESI+) *m*/*z* calcd for $C_{23}H_{22}N_4O_{11}Na$: 553.1177, found: 553.1173. IR (KBr): *v* 1088; 1180; 1233; 1346; 1451; 1538; 1593; 1614; 1713; 1742; 3090.

4.1.6. (Anthracen-10-yl)methyl 3-((*R*)-2-hydroxy-1-phenylethylcarbamoyl)propanoate 2b. $C_{27}H_{25}NO_4$ (427.49). 88% yield. Yellow powder. Mp = 160 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.48. ^{1}H NMR (250 MHz in $CDCl_3$): δ 2.50–2.60 (2H, m); 2.70–2.80 (2H, m); 3.81 (2H, br s); 4.90–5.10 (1H, m); 6.18 (2H, s); 6.42 (1H, br s); 7.40–7.50 (5H, m); 7.50–7.61 (4H, m); 8.04 (2H, d, ^3J = 9.8 Hz); 8.33 (2H, d, ^3J = 10.6 Hz); 8.50 (1H, s). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 29.4; 30.8; 55.7; 59.0; 66.2; 123.7; 123.9; 125.1; 125.6; 126.7; 127.9; 128.8; 129.1; 129.3; 131.0; 131.3; 138.8; 171.8; 173.2. MS (ESI+) *m*/*z* = 450.1 [M+Na$^+$] (100%). HRMS (ESI+) *m*/*z* calcd for $C_{27}H_{25}NO_4Na$: 450.1676, found : 450.1682. IR (KBr): *v* 1060; 1158; 1321; 1375; 1425; 1644; 1718; 2925; 3058; 3081; 3300.

4.1.7. 3-((*R*)-2-Hydroxy-1-phenylethylcarbamoyl)propyl 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylate 7b. $C_{26}H_{20}N_4O_{11}$ (564.46). 14% yield. Purple powder. Mp = 223 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.57. ^{1}H NMR (300 MHz in $CDCl_3$): δ 2.05–2.20 (2H, m); 2.36–2.48 (2H, m); 3.27 (1H, br s); 3.66–3.82 (2H, m); 4.48 (2H, t, ^3J = 6.0 Hz); 5.10–5.15 (1H, m); 6.75 (1H, d, ^3J = 7.3 Hz); 7.08–7.32 (5H, m); 8.63 (1H, s); 8.79 (2H, s); 8.88 (1H, s). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 24.3; 32.6; 55.5; 66.0; 66.7; 121.7; 122.4; 125.2; 126.5; 127.5;

128.5; 130.5; 131.9; 137.6; 138.7; 139.0; 139.5; 143.3; 146.3; 149.2; 149.4; 164.4; 172.3; 184.9. MS (ESI+) $m/z = 304.2$ (100%); 587.0 [M+Na^+] (46%). HRMS (ESI+) m/z calcd for $C_{26}H_{20}N_4O_{11}Na$: 587.1026, found: 587.1016. IR (KBr): ν 1742; 1088; 1180; 1233; 1346; 1451; 1538; 1593; 1614; 1615; 1713; 3090.

4.1.8. (Anthracen-10-yl)methyl 3-((*S*)-1-hydroxy-3,3-dimethylbutan-2-ylcarbamoyl)propanoate 2c. $C_{25}H_{29}NO_4$ (407.50). 31% yield. Yellow oil. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.56. ^1H NMR (250 MHz in $CDCl_3$): δ 0.88 (9H, s); 2.40–2.55 (2H, m); 2.60–2.75 (2H, m); 3.35–3.60 (1H, m); 3.70–3.90 (2H, m); 6.02 and 6.10 (2H, 2d, $^3J = 12.3$ Hz); 6.26 (1H, d, $^3J = 9.8$ Hz); 7.40–7.55 (4H, m); 7.91 (2H, d, $^3J = 8.2$ Hz); 8.25 (2H, d, $^3J = 8.9$ Hz); 8.36 (1H, s). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 26.6; 29.6; 31.0; 33.3; 59.0; 59.3; 62.1; 123.7; 124.9; 125.7; 126.4; 128.8; 129.0; 130.7; 131.1; 172.5; 173.3. MS (ESI+) m/z = 430.1 [M+Na^+] (100%). HRMS (ESI+) m/z calcd for $C_{25}H_{29}NO_4Na$: 430.1989, found: 430.1996. IR (CaF_2 in $CHCl_3$): ν 1048; 1250; 1390; 1450; 1602; 1720; 2976; 3443.

4.1.9. 3-((*S*)-1-Hydroxy-3,3-dimethylbutan-2-ylcarbamoyl)-propyl 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylate 7c. $C_{24}H_{24}N_4O_{11}$ (544.47). 67% yield. Purple powder. Mp = 163–164 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.61. ^1H NMR (360 MHz in $CDCl_3$): δ 0.94 (9H, s); 2.15–2.30 (2H, m); 2.50 (2H, t, $^3J = 7.2$ Hz); 3.45–3.65 (1H, m); 3.80–3.90 (2H, m); 4.40–4.55 (2H, m); 5.83 (1H, d, $^3J = 9.2$ Hz); 8.74 (1H, d, $^4J = 2.2$ Hz); 8.80 (1H, d, $^4J = 1.9$ Hz); 8.86 (1H, d, $^4J = 2.2$ Hz); 8.92 (1H, d, $^4J = 2.2$ Hz). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 24.8; 26.9; 33.0; 33.4; 59.6; 63.1; 66.9; 121.9; 122.6; 125.3; 130.7; 132.2; 137.8; 138.9; 139.1; 143.2; 146.7; 149.4; 149.6; 164.6; 173.0; 185.1. MS (ESI+) $m/z = 567.1$ [M+Na^+] (100%). HRMS (ESI+) m/z calcd for $C_{24}H_{24}N_4O_{11}Na$: 567.1334, found: 567.1337. IR (CaF_2 in $CHCl_3$): ν 1047; 1265; 1364; 1390; 1450; 1543; 1601; 1710; 1739; 2895; 2976.

4.1.10. Oxazolines: General cyclization procedure. In an oven-dried schlenck under an argon atmosphere, DAST (0.29 mL, 2.2 mmol, 1.1 equiv) was added dropwise to a cold (−78 °C) solution of β-hydroxamide (2.0 mmol, 1.0 equiv) in anhydrous CH_2Cl_2 (12 mL). After stirring for half an hour at −78 °C, anhydrous K_2CO_3 (0.4 g, 3.0 mmol, 1.5 equiv) was added in one portion and the mixture was allowed to warm to ambient temperature. The reaction was poured into saturated aqueous $NaHCO_3$ and the biphasic mixture was extracted with CH_2Cl_2. The combined organic extracts were dried over $MgSO_4$, filtered and concentrated in vacuum. Purification of the residue by chromatography on silica gel (AcOEt/cyclohexane, 20:80, Et_3N 1 mol %) led to the desired oxazoline.

4.1.11. (Anthracen-10-yl)methyl 3-((*S*)-4,5-dihydro-4-isopropyloxazol-2-yl)propanoate 3a. $C_{24}H_{25}NO_3$ (375.46). 80% yield. Yellow powder. Mp = 57–58 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.44. ^1H NMR (250 MHz in $CDCl_3$): δ 0.80 (3H, d, $^3J = 7.9$ Hz); 0.88 (3H, d, $^3J = 7.9$ Hz); 1.57–1.65 (1H, m), 2.58–2.61 (2H, m); 2.67–2.73 (2H, m); 3.71–3.83 (2H, m); 4.05–4.12 (1H, m); 6.15 (2H, s); 7.44–7.58 (4H, m); 7.98 (2H, d, $^3J = 7.6$ Hz); 8.33 (2H, d, $^3J = 8.2$ Hz); 8.44 (1H, s). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 17.9; 18.5; 23.1; 30.5; 32.3; 58.8; 69.9; 71.8; 123.8; 124.9; 126.0; 126.4; 128.9; 129.0; 130.9; 131.2; 165.5; 172.3. MS (ESI+) $m/z = 398.1$ [M+Na^+] (100%). HRMS (ESI+) m/z calcd for $C_{24}H_{25}NO_3Na$: 398.1727, found: 398.1729. IR (CaF_2 in $CHCl_3$): ν 1159; 1211; 1384; 1447; 1499; 1527; 1625; 1672; 1735; 2905; 3031. $[\alpha]_{589}^{25} = -28$; $[\alpha]_{436}^{25} = -56$ (c 0.5, $CHCl_3$).

4.1.12. 3-((*S*)-4,5-Dihydro-4-isopropyloxazol-2-yl)propyl 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylate 8a. $C_{23}H_{20}N_4O_{10}$ (512.43). 90% yield. Brown powder. Mp = 137–140 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.30. ^1H NMR (360 MHz in $CDCl_3$): δ 0.88 (3H, d, $^3J = 6.8$ Hz); 0.95 (3H, d, $^3J = 6.6$ Hz); 1.71–1.77 (1H, m); 2.10–2.25 (2H, m); 2.45–2.55 (2H, m); 3.85–4.10 (2H, m); 4.23 (1H, dd, $^2J = 7.9$ Hz, $^3J = 9.2$ Hz); 4.46 (2H, t, $^3J = 6.6$ Hz); 8.75–8.94 (4H, m). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 18.1; 18.7; 24.4; 25.0; 32.6; 66.6; 70.1; 72.1; 121.8; 122.5; 125.3; 130.5; 132.4; 137.8; 138.8; 139.7; 143.5; 146.7; 149.4; 149.6; 164.4; 166.0; 185.0. MS (ESI+) $m/z = 513.1$ [M+1] (100%); 535.1 [M+Na^+] (72%). HRMS (ESI+) m/z calcd for $C_{23}H_{21}N_4O_{10}$: 513.1252, found: 513.1255. IR (CaF_2 in $CHCl_3$): ν 1088; 1175; 1234; 1341; 1459; 1508; 1536; 1542; 1615; 1649; 1718; 1738; 2905; 3010. $[\alpha]_{589}^{25} = -35$; $[\alpha]_{436}^{25} = -102$ (c 0.3, $CHCl_3$).

4.1.13. (Anthracen-10-yl)methyl 3-((*R*)-4,5-dihydro-4-phenyloxazol-2-yl)propanoate 3b. $C_{27}H_{23}NO_3$ (409.48). 20% yield. Yellow oil. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.61. ^1H NMR (300 MHz in $CDCl_3$): δ 2.40–2.70 (4H, m); 3.85 (1H, dd, $^2J = {}^3J = 8.3$ Hz); 4.92 (1H, dd, $^2J = {}^3J = 8.5$ Hz); 4.92 (1H, dd, $^3J = {}^3J = 8.5$ Hz); 6.02 (2H, s); 6.90–7.30 (9H, m); 7.84 (2H, dd, $^4J = 1.7$ Hz, $^3J = 7.2$ Hz); 8.18 (2H, d, $^3J = 8.7$ Hz); 8.30 (1H, s). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 24.6; 32.7; 65.2; 66.8; 73.6; 121.8; 122.5; 124.4; 125.3; 125.3; 127.2; 128.3; 130.6; 132.2; 137.7; 138.8; 139.9; 140.4. MS (ESI+) $m/z = 432.1$ [M+Na^+] (100%). HRMS (ESI+) m/z calcd for $C_{27}H_{23}NO_3Na$: 432.1576, found: 432.1561. IR (CaF_2 in $CHCl_3$): ν 1156; 1210; 1383; 1448; 1494; 1527; 1603; 1668; 1732; 2925; 3030; 3059. $[\alpha]_{589}^{25} = +12$; $[\alpha]_{436}^{25} = +24$ (c 0.6, $CHCl_3$).

4.1.14. 3-((*R*)-4,5-Dihydro-4-phenyloxazol-2-yl)propyl 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylate 8b. $C_{26}H_{18}N_4O_{10}$ (546.44). 28% yield. Purple powder. Mp = 85 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.75. NMR ^1H (360 MHz in $CDCl_3$): δ 2.24–2.28 (2H, m); 2.59 (2H, t, $^3J = 6.9$ Hz); 4.09–4.13 (1H, m); 4.52 (2H, t, $^3J = 6.4$ Hz); 4.60–4.70 (1H, m); 5.19 (1H, t, $^3J = 8.5$ Hz); 7.22–7.35 (5H, m); 8.74 (1H, d, $^3J = 2.2$ Hz); 8.81 (1H, d, $^3J = 2.2$ Hz); 8.85 (1H, d, $^3J = 2.2$ Hz); 8.94 (1H, d, $^3J = 2.2$ Hz). NMR ^{13}C (62.5 MHz in $CDCl_3$): δ 24.4; 24.9; 66.6; 69.6; 74.7; 121.8; 122.4; 125.2; 126.5; 127.5; 128.7; 130.5; 132.3; 137.7; 138.8; 139.7; 142.1; 143.5; 146.6; 149.3; 149.6; 164.5; 167.5; 185.0. MS (ESI+) m/z = 547.1 [M+1] (100%); 569.0 [M+Na^+] (66%). HRMS (ESI+) m/z calcd for $C_{26}H_{19}N_4O_{10}$: 547.1096, found: 547.1106. IR (CaF_2 in $CHCl_3$): ν 1041; 1089; 1174; 1345;

1480; 1538; 1595; 1615; 1663; 1720; 1738; 2895; 3010. $[\alpha]_{589}^{25} = +33$ (*c* 0.4, $CHCl_3$).

4.1.15. (Anthracen-10-yl)methyl 3-((*S*)-4-*tert*-butyl-4,5-dihydrooxazol-2-yl)propanoate 3c. $C_{25}H_{27}NO_3$ (389.49). 98% yield. Yellow oil. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.50. ^1H NMR (300 MHz in $CDCl_3$): δ 0.79 (9H, s); 2.40–2.75 (4H, m); 3.55–3.70 (1H, m); 3.85–4.05 (2H, m); 6.07 (2H, s); 7.30–7.55 (4H, m); 7.88 (2H, d, $^3J = 8.3$ Hz); 8.20–8.35 (3H, m). ^{13}C NMR (90 MHz in $CDCl_3$): δ 22.9; 25.3; 30.3; 33.1; 58.5; 68.2; 75.2; 123.6; 124.7; 125.9; 126.2; 128.7; 128.8; 130.7; 131.0; 165.3; 172.0. MS (ESI+) *m*/*z* = 389.2 (32%). HRMS (EI) *m*/*z* calcd for $C_{25}H_{27}NO_3$: 389.1985, found: 389.1984. IR (CaF_2 in $CHCl_3$): *v* 1156; 1210; 1383; 1448; 1494; 1527; 1603; 1668; 1732; 2925; 3030; 3059. $[\alpha]_{589}^{25} = -2$; $[\alpha]_{436}^{25} = -6$ (*c* 0.4; $CHCl_3$).

4.1.16. 3-((*S*)-4-*tert*-Butyl-4,5-dihydrooxazol-2-yl)propyl 2,5,7-trinitro-9-oxo-9*H*-fluorene-4-carboxylate 8c. $C_{24}H_{22}N_4O_{10}$ (526.45). 88% yield. Purple powder. Mp = 135–140 °C. R_f (in AcOEt/cyclohexane, 40/60 + 1% Et_3N) = 0.61. ^1H NMR (250 MHz in $CDCl_3$): δ 0.87 (9H, s); 2.05–2.20 (2H, m); 2.40–2.55 (2H, m); 3.70–3.85 (1H, m); 4.03 (1H, dd, $^2J = {}^3J = 8.5$ Hz); 4.16 (1H, dd, $^3J = 8.5$ Hz; $^2J = 10.1$ Hz); 4.43 (2H, t, $^3J = 6.6$ Hz); 8.72 (1H, d, $^4J = 2.2$ Hz); 8.78 (1H, d, $^4J = 1.9$ Hz); 8.80 (1H, d, $^4J = 2.2$ Hz); 8.90 (1H, d, $^4J = 2.2$ Hz). ^{13}C NMR (62.5 MHz in $CDCl_3$): δ 24.2; 24.9; 25.6; 33.4; 66.4; 68.5; 75.5; 121.6; 122.3; 125.2; 130.4; 132.1; 137.6; 138.7; 139.6; 143.4; 146.5; 149.2; 149.4; 164.2; 165.8. 184.9. MS (ESI+) *m*/*z* = 527.1 [M+1] (100%); 549.1 [M+Na^+] (42%). HRMS (ESI) *m*/*z* calcd for $C_{24}H_{23}N_4O_{10}$: 527.1409, found: 527.1418. IR (KBr): *v* 1089; 1161; 1231; 1341; 1458; 1541; 1595; 1616; 1672; 1723; 1744; 2961; 3030. $[\alpha]_{589}^{25} = -29$; $[\alpha]_{436}^{25} = -74$ (*c* 0.5; $CHCl_3$).

4.2. Catalytic tests

A schlenk tube was charged with $Cu(OTf)_2$ (see the quantities specified in each table) under argon. The combined ligands (see tables) dissolved in CH_2Cl_2 (500 μL) were added dropwise, and the complex was stirred for 3 h at room temperature, and then cooled at the desired temperature. 3-But-2-enoyl-oxazolidin-2-one (51 mg, 0.33 mmol, 1.0 equiv) dissolved in CH_2Cl_2 (250 μL) was added via syringe, followed by freshly cracked cyclopentadiene (200 μL, 2.4 mmol, 7.2 equiv). When the reaction was finished, pentane (10 mL) was added to precipitate the complex. The product solution was removed from the reaction vessel, and the precipitate was washed twice more with pentane before its reuse. The product solution is hydrolyzed with a sat. NH_4Cl solution (2 mL) and extracted with CH_2Cl_2. The combined organic layers are dried over $MgSO_4$ and the products are purified on preparative TLC (toluene/ethyl acetate 80/20).

4.2.1. 3-[[3-Methylbicyclo[2.2.1]hept-5-en-2-yl]carbonyl]-oxazolidin-2-one (*endolexo* mixture). ^1H NMR (360 MHz in $CDCl_3$): δ 0.87 (3H, d, $^3J = 7.0$ Hz, *exo*); 1.13 (3 H, d, $^3J = 7.0$ Hz, *endo*); 1.48 (1H, d, $^3J = 8.4$ Hz); 1.66 (1H, d, $^3J = 8.6$ Hz); 2.02–2.15 (1H, m); 2.53 (1H, br s); 3.25 (1H, br s); 3.49–3.55 (1H, m); 3.87–4.08 (2H, m); 4.39 (2H, dd, $^3J = 8.1$ Hz, $^3J = 8.1$ Hz); 5.78 (1H, dd, $^3J = 5.6$ Hz, $^3J = 2.9$ Hz, *endo*); 6.15 (1H, dd, $^3J = 5.7$ Hz, $^3J = 3.0$ Hz, *exo*); 6.31 (1H, dd, $^3J = 5.7$ Hz, $^3J = 3.1$ Hz, *exo*); 6.43 (1H, dd, $^3J = 5.7$ Hz, $^3J = 2.9$ Hz, *endo*).

HPLC (Whelk 01, hexane/EtOH (99/1), flow: 0.8 mL min^{-1}, $\lambda = 215$ nm): tr = 36.4 min (*exo* (2*R*)), tr = 38.2 min (*exo* (2*S*)), tr = 41.2 min (*endo* (2*S*)), tr = 44.7 min (*endo* (2*R*)). The configurations were assigned by injections on an IA column (and comparison with the literature).[21]

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