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Biphasic Enantioselective Olefin Epoxidation Using *Tropos* Dibenzoazepinium Catalysts

Jérôme Vachon,[†] Céline Pérollier,[†] David Monchaud,[†] Claire Marsol,[†] Klaus Ditrich,[§] and Jérôme Lacour*,[†]

Département de Chimie Organique, Université de Genève, quai Ernest-Ansermet 30, CH-1211 Genève 4, Switzerland, and BASF Aktiengesellschaft, Forschung Feinchemikalien & Biokatalyse, 67056 Ludwigshafen, Germany

Jerome.Lacour@chiorg.unige.ch

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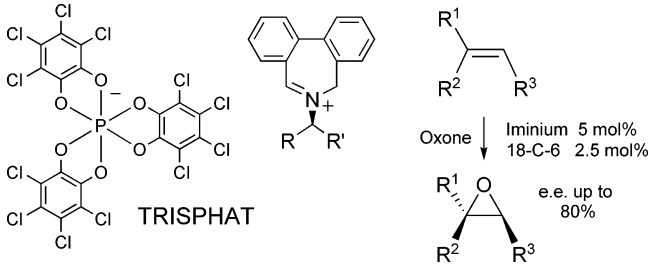

Several novel chiral iminium TRISPHAT [tris(tetrachlorobenzenediolato)phosphate(V)] salts combining a diphenylazepinium core, chiral exocyclic appendages, and lipophilic counterions have been prepared and tested in biphasic enantioselective olefin epoxidation conditions. Interestingly, the iminium salts derived from commercially available (*S*)- or (*R*)-1,2,2-trimethylpropylamine can display efficiency similar to those made from L-acetonamine. Variable-temperature NMR spectroscopy (VT-NMR) and circular dichroism (CD) experiments were performed in search of a correlation between good enantioselectivity in the products and high diastereomeric control of the biphenyl axial chirality of the catalysts.

Chiral epoxides are not only useful precursors for organic chemists but are also useful for frequently met structures in natural products in relation to their biological activities.[1] Quite a few efficient methods exist for their preparation from olefins, and many of them use transition-metal catalysts such as the Katsuki−Sharpless or Katsuki−Jacobsen protocols.[2] In recent years, much effort has been devoted to the development of organocatalyzed epoxidation conditions that afford metal-free procedures; the catalysts are perhydrate, ketone or oxaziridine, and amine moieties as well as oxoammonium or iminium salts.[3,4]

Ketone-catalyzed epoxidation of olefins using Oxone ($KHSO_5 \cdot KHSO_4 \cdot K_2SO_4$) as a stoichiometric oxidant has been particularly studied.[5] High degrees of selectivity have been achieved using, for instance, 11-membered ring C_2-symmetric α,α′-diacyloxyketone[6] or fructose-derived cyclohexanones as catalysts.[5c,7] These efficient ketone-mediated reactions often need to be carefully monitored, as moving a few tenths of a unit away from a 7.8−8.0 pH region may lead to a rapid decomposition of the hydrogen persulfate oxidant in basic conditions (pH > 8). Although, on the contrary, if lower pH conditions (pH < 7.5) are used or obtained during the course of the reaction, then a rapid decomposition of the ketone

[†] Université de Genève.

[§] BASF Aktiengesellschaft, Forschung Feinchemikalien & Biokatalyse.

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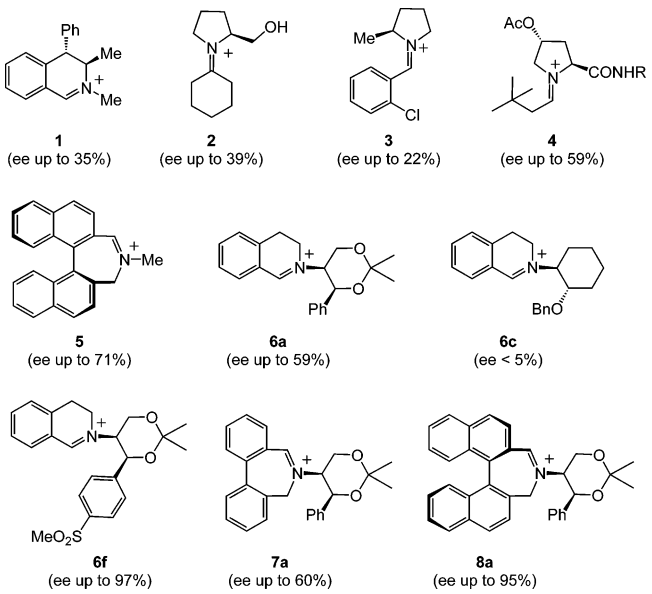

FIGURE 1. Known iminium nonracemic catalysts and highest enantiomeric excesses achieved.

catalysts is observed via Baeyer−Villiger, similar to oxidation of the carbonyl moieties.[8,9]

Iminium salts are an interesting alternative to ketones. These compounds are effective oxygen-transfer reagents toward nucleophilic substrates and electron-rich unfunctionalized olefins, in particular. Moreover, the propensity of oxaziridinium species to be readily prepared by the reaction of iminium ions with Oxone renders the development of catalytic processes possible.[10] The first example of an asymmetric iminium-catalyzed reaction was reported in 1993 using dihydroisoquinolinium cation **1** as a catalyst (Figure 1); this system has been inspired by the studies of the Orsay group since 1976.[11,12] The reaction conditions (solvent, temperature) were later optimized, and the mechanism was further studied.[13] Since this pioneering work, several groups have proposed successful enantioselective variants (Figure 1).

There are essentially two classes of nonracemic iminium ion catalysts. One class is constituted of exocyclic chiral iminium salts such as compounds [**2**][BF_4],[14] [**3**][ClO_4],[15] and [**4**][X][16] made by the condensation of enantiopure pyrrolidine moieties with aldehydes or ketones. Decent levels of stereoselective induction were obtained using these cations (enantiomeric excess (ee) up to 59% with compound **4** on *trans*-stilbene). Rather high catalyst loading is unfortunately required (10 mol % for **2**, 100 mol % for **3**, and between 20 and 50 mol % for **4**) due probably to in-situ hydrolysis of the iminium moieties under the aqueous reaction conditions.

The second class involves endocyclic chiral iminium salts. As mentioned before, the first nonracemic example was salt [**1**][BF_4].[11] Using this derivative, a modest level of selectivity was achieved (ee up to 35%). In 1996, Aggarwal and co-workers reported axially chiral, configurationally stable, binaphthyl-derived catalyst [**5**][BF_4]; this compound is particularly efficient for the epoxidation of 1-phenylcyclohexene (71% ee).[17] A mechanistic rationale was proposed to explain the absolute sense of configuration of the resulting epoxides.[18] In 1998, Page and co-workers modified the core structure of catalyst **1** by introducing stereogenic elements outside rather than inside of the six-membered ring heterocycle.[19] A strong influence of the chiral appendage was noticed, as L-(+)-acetonamine[20] derived iminium **6a** displayed quite higher selectivity than, for instance, **6c** made from (1*S*,2*S*)-2-benzyloxycyclohexylamine (ee 41% and <5%, respectively, with 1-phenyl-cyclohexene). Very recently, Page and co-workers reported a modification of catalyst **6a** carrying a *para*-methylsulfonyl group (iminium **6f**) that behaves as a very efficient asymmetric catalyst for benzopyran derivatives, in particular.[21]

A second generation of iminium catalysts with exocyclic chiral appendages was later developed independently by the groups of Loughborough[22] and our own.[23] These catalysts utilize the same diphenylazepinium cation **7a** derived from D-(−)- or L-(+)-acetonamine and differ only by the nature of the counterion BPh_4^- and TRISPHAT [tris(tetrachlorobenzenediolato)phosphate(V)], respectively.[24] Unlike derivatives **6a**, **6c**, and **6f**, compound **7a** possesses a cyclic skeleton, which is chiral. Literature precedents show that biphenyl species of this type exist as two atropisomers (*R*a and *S*a) that interconvert freely in solution by rotation around the stereogenic axis.[25] Direct comparison of the BPh_4 salts of seven-membered ring **7a** and six-membered **6a** showed that most of the

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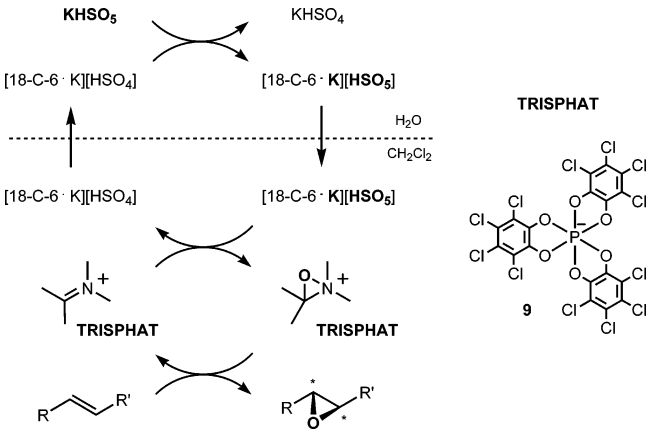

FIGURE 2. Proposed catalytic cycle of biphasic epoxidation reaction.

reaction rates, conversions, and enantioselectivities were enhanced by the use of the larger ring size catalysts.[22] Recently, Page and co-workers were able to synthesize and isolate three enantiopure forms of the four possible stereoisomers of **8a** which combine Aggarwal's conformationally rigid dinaphthazepinium skeleton (*R*a and *S*a atropisomers) with Page's L-(+)- or D-(−)-acetonamine moiety.[17,19] Only one pair of enantiomeric catalysts, (*R*a, L) and (*S*a, D), displayed high reactivity and selectivity (up to 95% ee for the epoxidation of 1-phenyl-3,4-dihydronaphthalene); the mismatched diastereomers lead to essentially poor conversions under the same reaction conditions.

Traditionally, the epoxidation reactions are performed in mixtures of CH_3CN and water. This combination is a good solvent for all reagents, including the lipophilic olefins as well as the polar BF_4^- or PF_6^- salts of iminium cations.[17] Previously, using salt [**7a**][TRISPHAT] (Figure 2), strict biphasic CH_2Cl_2/water conditions could be used and an enhancement of the selectivity of the epoxidation reaction as well as a good recovery of the epoxides was demonstrated.[23] In fact, the lipophilicity of TRISPHAT anion **9** confers to its salts an affinity for organic solvents and, once dissolved, the ion pairs do not partition in aqueous layers. Consequently, a tight containment of the reagents in two liquid phases occurs, with the organic TRISPHAT salts in the organic layer and Oxone in the aqueous phase. Addition of a catalytic amount of 18-Crown-6 (2.5 mol %) establishes a transport mechanism of $KHSO_5/KHSO_4$ between aqueous and organic layers and permits the oxidation in CH_2Cl_2 of the iminium cation into the reactive oxaziridinium form (Figure 2). As mentioned, slightly better results were obtained using these conditions, in which the oxidation occurs only in the CH_2Cl_2 phase.[26] A similar observation was recently reported by Page and co-workers who developed strict anhydrous conditions using pure CH_2Cl_2 as solvent and tetraphenylphosphonium monoperoxybisulfate (TPPP) as a stoichiometric oxidant. The reactions can now be

(26) One can wonder whether the increased stereoselectivity of the epoxidation reaction in less polar CH_2Cl_2 vs CH_3CN results from a "destabilization" of the cationic spiro diastereomeric transition states and, hence, in more discriminating stereoselective interactions.

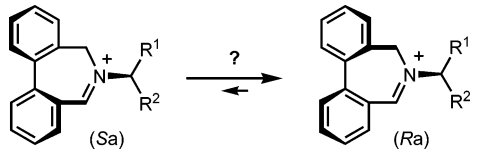

FIGURE 3. Possible stereocontrol by chiral exocyclic appendages.

performed at −40 °C, and a further increase in selectivity was observed for some substrates.[21,27]

For the initial selection of nonracemic catalyst of type **6a**, a rather extensive screening of chiral exocyclic appendages was performed by Page and co-workers.[19] Many enantiopure primary amine precursors were attached to the dihydroisoquinolinium skeleton, and the resulting compounds were tested. For the diphenylazepinium systems, with the exception of (−)-isopinocampheylamine which leads to a less selective catalyst than L-(+)-acetonamine, no other chiral appendage has been reported to date. With the twisted seven-membered ring of **7a** being sufficiently different from the "planar" dihydroisoquinolinium framework of **6**, it was debatable whether L-(+)-acetonamine was the best auxiliary in this case. Herein, we report a series of novel diphenylazepinium moieties (**7b**−**e**) prepared from commercially available, nonracemic primary amines and a comparison of their efficiency in biphasic TRISPHAT mediated epoxidation reactions.

As already mentioned, two atropisomeric conformations exist for the seven-membered ring backbone of catalysts **7a**−**e**. The presence of the chiral exocyclic auxiliaries results in the formation of diastereomeric structures that equilibrate rapidly in solution with, possibly, a drift of the conformational equilibrium toward one preferred (*R*a) or (*S*a) diastereomer as a consequence of intramolecular discriminating interactions (Figure 3).[28] Care was thus taken in this study to characterize the structure of the diphenylazepinium cations by variable-temperature NMR spectroscopy (VT-NMR) and circular dichroism (CD) in search of a correlation between good enantioselectivity in the products and high diastereomeric control of the biphenyl axial chirality of the catalysts.

Results and Discussion

Catalyst Preparation. One of our goals was thus to vary the nature of the chiral appendage linked to the diphenylazepinium catalytic framework of **7**. Care was taken to select, in addition to L-(+)-acetonamine **a**, acyclic and cyclic amines that were commercially available in both enantiomeric forms. For the initial screening, we arbitrarily selected the enantiomers of amines **a**−**e** carrying (*S*) stereogenic centers at the carbon α to the sp^2 nitrogen atom. These amines are detailed in Figure 4. Only compound **7b** was prepared in both enantiomeric forms, for reasons that will be detailed later.

Synthesis of the derived diphenylazepinium catalysts **7a**−**e** was realized in three steps, following a general and reproducible protocol. After the ozonolysis of phenan-

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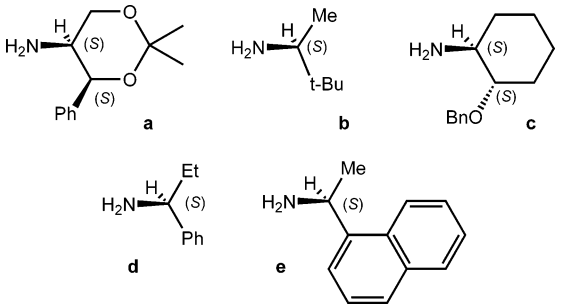
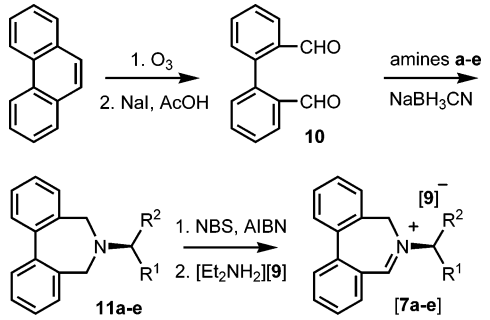


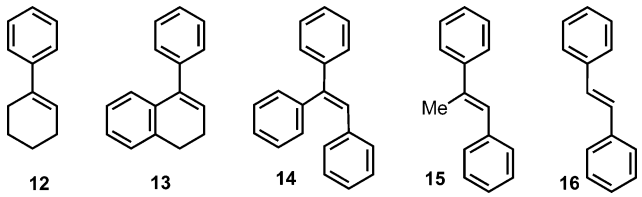
FIGURE 4. Selected amines for the formation of catalysts **7a**−**e**.

SCHEME 1. Synthesis of Catalysts [7a][9] to [7e][9]



threne (ozone, NaI, AcOH), giving biphenyl-2,2′-dicarbaldehyde **10** (61%),[29] and reductive amination in the presence of enantiopure amines **a**−**e**, $NaBH_3CN$, and AcOH, the desired compounds **11a**−**e** were afforded in decent to good yields (70−83%). Oxidation of the azepines with NBS and a catalytic amount of AIBN in CCl_4 at 20 °C afforded the diphenylazepinium ions as their bromide salts;[30] this milder room-temperature protocol is preferred to the I_2/KOAc procedure.[23,31] The crude reaction mixtures were directly submitted to ion-exchange metathesis with 1.2 equiv of the racemic $[Et_2NH_2]$[TRISPHAT] salt, $[Et_2NH_2]$[**9**]. The lipophilicity of TRISPHAT anion **9** modified profoundly the chromatographic properties of cations associated with it, and the resulting ion pairs, [**7a**][**9**] to [**7e**][**9**], were poorly retained on polar chromatographic phase (Al_2O_3, pH 9.9, CH_2Cl_2), allowing their isolation in modest to decent yields (Scheme **1**, 50−66%).[32]

Catalysis. Catalysts [**7a**][**9**] to [**7e**][**9**] were then tested using the biphasic CH_2Cl_2/water/18-C-6 protocol detailed previously.[23] Prochiral di- and trisubstituted unfunctionalized alkenes **12**−**16** were used as substrates, and the results are reported in Table 1.



Significantly, catalyst [**7b**][**9**], in which (*S*)-1,2,2-trimethylpropylamine **b** has replaced the L-(+)-acetonamine **a** moiety, shows results comparable to those of iminium salt [**7a**][**9**] in conversions and enantioselectivity. With olefins **12**−**16**, these two catalysts afford epoxides of the same absolute configurations. As can be expected, the opposite sense of induction was obtained when the catalyst made from the (*R*)-1,2,2-trimethylpropylamine, [*ent*-**7b**][**9**], was used. Compound [**7c**][**9**] leads to slightly lower enantioselectivities (from 76 to 62% ee from olefin **13**). This catalyst, derived from (1*S*,2*S*)-2-benzyloxycyclohexylamine **c**, is, however, quite more efficient than the previously reported **6c**. Catalysts [**7d**][**9**] and [**7e**][**9**] that contain stereogenic centers α to the nitrogen atom, bearing a small alkyl chain (Me, Et) and an aromatic group (1-naphthyl, phenyl), afford epoxides with a drastic decrease of the enantioselectivity (for olefin **13**, 29 and 3% ee, respectively), although with a decent amount of conversions. Generally, the best results were obtained with 1-phenyl-3,4-dihydronaphthalene **13** as a substrate. Finally, catalysts [**7b**][**9**] and [**7d**][**9**], albeit both prepared from *S*-configured acyclic α-branched amines, afford the epoxide of olefin **12** with opposite configurations, (−)-(1*S*,2*S*)- and (+)-(1*R*,2*R*)-1-phenylcyclohex-1-ene oxide, respectively (Table 1).[33] The same observation can be made for the oxidation product of **13**.

The effect of the temperature was studied with catalysts [**7a**][**9**] to [**7e**][**9**] because, as Page and co-workers have observed, a lower temperature can lead to an increase in the enantioselectivity of the epoxidation reaction.[27] Because of the presence of water in the biphasic CH_2Cl_2/water/18-C-6 protocol, we could not reach very low temperatures. The presence of 4 equiv of $NaHCO_3$ (1.0 M) and 1.1 equiv of Oxone (0.27 M) saturated the aqueous phase, and the experiments could be performed at −5 °C as a lower limit.[34] However, for practical reasons, most experiments were carried out at 0 °C; all reagents were soluble in both phases. Catalyst [**7b**][**9**] was selected for the initial screening, and the results of the reactions of olefins **12**−**16** with Oxone in its presence are summarized in Table 2. Using the same time frame (2 h) as was used for the reactions at room temperature, we observed, in the particular case of 1-phenyl-3,4-dihydronaphthalene **13**, quite better conversions (100% vs 72% at 20 °C) and ee's (80% vs 70%). No significant improvement was noticed with the other olefins.

With these results in hand, the study was continued at four different temperatures using the better substrate, **13**, and catalyst [**7b**][**9**] (Table 3). Good conversions were always obtained using temperatures from 4 to −5 °C. For the enantioselectivity, a moderate but definite increase in asymmetric induction was obtained at each decreasing-temperature step.

Finally, all iminium catalysts, [**7a**][**9**] to [**7e**][**9**], were tested using substrate **13** under the biphasic conditions at 0 °C, and the results are reported in Table 4.

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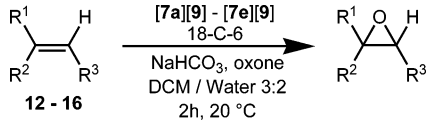
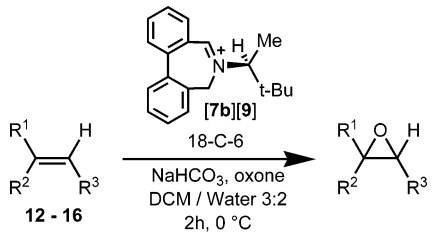
TABLE 1. Epoxidation of Olefins at 20 °C Using Catalysts [7a][9] to [7e][9][a]



catalyst	results	**12**	**13**	**14**	**15**	**16**
[**7a**][**9**]	ee %[c]	69[d]	76	23	42	17
	conversion %[b]	100[f]	85	82	80	67
	configuration	(−)-(1*S*,2*S*)	(+)-(1*R*,2*S*)	(+)-(*S*)	(−)-(1*S*,2*S*)	(−)-(*S*,*S*)
[**7b**][**9**]	ee %[c]	65[d]	70	29	41	14
	conversion %[b]	100[f]	72	69	84	62
	configuration	(−)-(1*S*,2*S*)	(+)-(1*R*,2*S*)	(+)-(*S*)	(−)-(1*S*,2*S*)	(−)-(*S*,*S*)
[*ent*-**7b**][**9**]	ee %[c]		70	28	40	
	conversion %[b]		63	79	94	
	configuration		(−)-(1*S*,2*R*)	(−)-(*R*)	(+)-(1*R*,2*R*)	
[**7c**][**9**]	ee %[c]	55[d]	62	17	25	6
	conversion %[b]	100[f]	68	70	81	61
	configuration	(−)-(1*S*,2*S*)	(+)-(1*R*,2*S*)	(+)-(*S*)	(−)-(1*S*,2*S*)	(−)-(*S*,*S*)
[**7d**][**9**]	ee %[c]	21[d]	29	2	5	4
	conversion %[b]	87[f]	66	57	53	48
	configuration	(+)-(1*R*,2*R*)	(−)-(1*S*,2*R*)	*e*	*e*	*e*
[**7e**][**9**]	ee %[c]	5[d]	3	7	10	3
	conversion %[b]	50[f]	62	58	70	57
	configuration	*e*	*e*	(+)-(*S*)	(−)-(1*S*,2*S*)	*e*

[a] Conditions: 5 mol % catalyst [**7a**][**9**] to [**7e**][**9**], 2.5 mol % 18-C-6, 1.1 equiv of Oxone, 4.0 equiv of $NaHCO_3$, CH_2Cl_2/H_2O (3:2), 20 °C, 2 h. Average of at least two runs. [b] Conversion calculated using naphthalene as an internal standard unless otherwise stated. [c] Determined by CSP−HPLC (Chiralcel OD−H) unless otherwise stated. [d] Determined by CSP−GC (Chiraldex Hydrodex β-3P). [e] Enantiomeric excesses too low to allow a precise determination of the absolute configuration. [f] Conversion calculated with dodecane as an internal reference.

TABLE 2. Low-Temperature (0 °C) Epoxidation of 12−16 in the Presence of [7b][9][a]



	0 °C		20 °C	
olefin	ee %[c]	conversion %[b]	ee %[c]	conversion %[b]
12	66[d]	68[e]	65[d]	100[e]
13	80	100	70	72
14	31	61	29	69
15	46	75	41	84
16	17	64	14	62

[a] Conditions: 5 mol % catalyst [**7b**][**9**], 2.5 mol % 18-C-6, 1.1 equiv of Oxone, 4.0 equiv of $NaHCO_3$, CH_2Cl_2/H_2O (3:2), 2 h. Average of at least two runs. [b] Conversion was calculated using an internal standard (naphthalene) unless otherwise stated. [c] Determined by CSP−HPLC (Chiralcel OD−H) unless otherwise stated. [d] Determined by CSP−GC (Chiraldex Hydrodex β-3P). [e] Conversion calculated with dodecane as an internal reference.

In general, conversions were better at 0 °C than at room temperature. Better ee's were measured in all cases. Interestingly, catalyst [**7b**][**9**] leads to essentially the same ee at 0 °C as[**7a**][**9**], whereas a noticeable difference was observed at room temperature.

Discussion

As already mentioned, two atropisomeric conformations exist for the seven-membered ring backbone of catalysts **7a**−**e**. Diphenylazepines of type **11**, precursors to compounds **7**, are known to undergo rapid conformational equilibration in solution with energy barriers ($\Delta G^{\ddagger}$) in the range of 12−14 kcal/mol^{-1}.[25,35] Even faster equilibration was possible for iminium derivatives **7** in view of literature precedents, indicating that a change of hybridization of two atoms from sp^3 to sp^2 within seven-membered diphenyl ring frameworks usually enhances the rate of rotation around the biaryl bond.[36] Because of the presence of the chiral appendages resulting in the formation of diastereomeric structures, the possibility of a nonequal distribution of the (*R*a) and (*S*a) diastereomers was considered. Care was thus taken to characterize the structure of the diphenylazepinium cations by VT-NMR and CD in search of a possible correlation between good enantioselectivity in the products and high diastereomeric control of the biphenyl axial chirality of the catalysts.

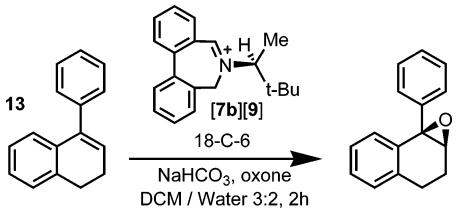
^{1}H NMR analysis of salts [**7c**][**9**], [**7d**][**9**], and [**7e**][**9**] confirmed the postulated assumption of a fast equilibrium among diastereomeric (*R*a) and (*S*a) structures as single (broad) and double (sharp) sets of signals were observed for these systems at 298 and 233 K, respectively. The signal of the iminium proton (δ 8.7−10.0-ppm region) was particularly useful to monitor the stereodynamics (Figure 5). Two signals appeared at 233 K due to a relatively slow interconversion of the atropisomers

(34) Solubilities in water: (a) $NaHCO_3$ at 0 and 20 °C, 0.82 and 1.14 mmol/mL^{-1}, respectively; (b) Oxone at 20 °C, 0.42 mmol/mL^{-1}.

(35) Rashidi-Ranjbar, P.; Taghvaei-Ganjali, S.; Wang, S. L.; Liao, F. L.; Heydari, A. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1255−1260. Superchi, S.; Casarini, D.; Laurita, A.; Bavoso, A.; Rosini, C. *Angew. Chem., Int. Ed.* **2001**, *40*, 451−454. Saudan, L. A.; Bernardinelli, G.; Kundig, E. P. *Synlett* **2000**, 483−486. Tichy, M.; Budesinsky, M.; Gunterova, J.; Zavada, J.; Podlaha, J.; Cisarova, I. *Tetrahedron* **1999**, *55*, 7893−7906. Kiupel, B.; Niederalt, C.; Nieger, M.; Grimme, S.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 3031−3034. Sutherland, I. O.; Ramsay, M. V. J. *Tetrahedron* **1965**, *21*, 3401−3408.

(36) Tichy, M.; Ridvan, L.; Holy, P.; Zavada, J.; Cisarova, I.; Podlaha, J. *Tetrahedron: Asymmetry* **1998**, *9*, 227−234 and references therein.

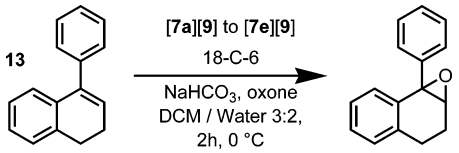
TABLE 3. Temperature Effect on the Epoxidation of 13 by Oxone in the Presence of [7b][9][a]



temperature	25 °C	4 °C	0 °C	−5 °C
ee %[b]	70	76	80	81
conversion %[c]	72	100	100	100
configuration	(+)-(1*R*, 2*S*)	(+)-(1*R*, 2*S*)	(+)-(1*R*, 2*S*)	(+)-(1*R*, 2*S*)

[a] Conditions: 5 mol % catalyst [**7b**][**9**], 2.5 mol % 18-C-6, 1.1 equiv of Oxone, 4.0 equiv of $NaHCO_3$, CH_2Cl_2/H_2O (3:2), 2 h. Average of at least two runs. [b] Determined by CSP−HPLC (Chiralcel OD−H). [c] Conversion was calculated using an internal standard (naphthalene).

TABLE 4. Low-Temperature (0 °C) Epoxidation of 13 by Oxone: Catalyst Study[a]



	0 °C		20 °C	
catalyst	ee %[b]	conversion %[c]	ee %[b]	conversion %[c]
[**7a**][**9**]	79	91	76	84
[**7b**][**9**]	80	100	70	72
[**7c**][**9**]	70	94	62	68
[**7d**][**9**]	35	92	29	66
[**7e**][**9**]	7	100	3	62

[a] Conditions: 5 mol % catalyst [**7a**][**9**] to [**7e**][**9**], 2.5 mol % 18-C-6, 1.1 equiv of Oxone, 4.0 equiv of $NaHCO_3$, CH_2Cl_2/H_2O (3:2), 2 h. Average of at least two runs. [b] Determined by CSP−HPLC (Chiralcel OD−H). [c] Conversion was calculated using an internal standard (naphthalene).

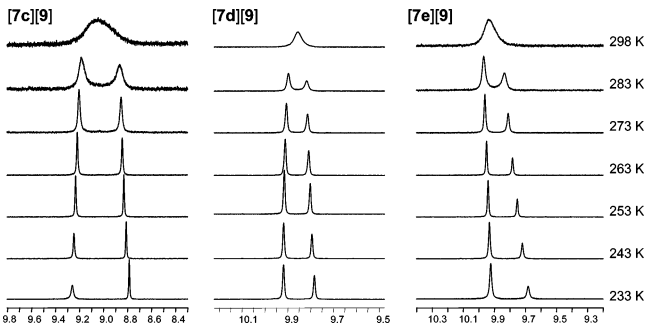


FIGURE 5. VT-NMR (500 MHz, CD_2Cl_2) of salts [**7c**][**9**], [**7d**][**9**], and [**7e**][**9**] and resulting diastereoselectivity (233 K; diastereomeric ratio 50:50, 59:41, 69:31, respectively).

on the NMR time scale and collapse with increasing temperature. Compounds [**7c**][**9**], [**7d**][**9**], and [**7e**][**9**] thus behaved as expected. Low diastereomeric enrichment (dr from 50:50 to 69:31) was observed because ratios between the (*S*a) and (*R*a) atropisomers could be measured by integration of the signals at 233 K and these are reported in Table 5. If one considers that NMR coalescence is reached at 298 K for these three systems, then approximate energy barriers in the range of 12−14 kcal/mol^{-1} can be rapidly estimated.[37]

Salts [**7a**][**9**] and [**7b**][**9**] present a more complex behavior and, at first sight, a rather puzzling NMR

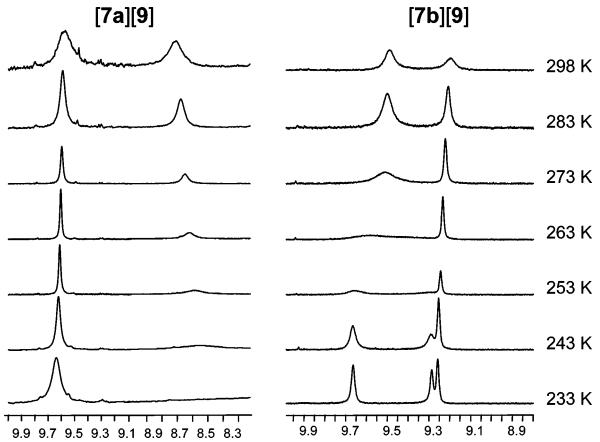


FIGURE 6. VT-NMR (CD_2Cl_2) of salts [**7a**][**9**] (500 MHz) and [**7b**][**9**] (400 MHz).

TABLE 5. Diastereomeric Ratios and Excesses (233 K), Rotamer Ratios (298 K), Cotton Effects (Δε), and Enantiomeric Excesses for the Oxidation of 13 with Catalysts [7a][9] to [7e][9] at 0 °C

					epoxide from **13**	
compound	dr	de %	rr	Δε (357 nm)	ee %	configuration
[**7a**][**9**]			52:48	0.5	79	(+)-(1*R*,2S)
[**7b**][**9**]	56:44	8	60:40	1.7	80	(+)-(1*R*,2S)
[**7c**][**9**]	50:50	0		3.4	70	(+)-(1*R*,2S)
[**7d**][**9**]	59:41	18		0.5	35	(−)-(1*S*,2R)
[**7e**][**9**]	69:31	28		0.0	6	(+)-(1*R*,2S)

situation (Figure 6). At 298 K, both spectra present two broad signals in the iminium region, whereas only one is observed for salts of cations **7c**, **7d**, and **7e**. When the temperature is lowered, one signal becomes sharp whereas the others broaden or split in two. A total of three signals is observed for [**7b**][**9**] at 233 K. This behavior is not accountable by the previous analysis of just two diastereomeric structures occurring at 233 K.

Previously, we and others have shown that slow rotation around N(sp^2)−C(sp^3, tertiary) bonds can occur when bulky substituents (R^1, R^2 (Figure 7)) are attached to the carbon.[38,39] For some acridinium derivatives, rotation barriers of 18.2, 20.1, and 16.7 kcal/mol^{-1} were

(37) The relationship $\Delta G^{\ddagger} = RT_c\,(22.96 + \ln(T_c/\Delta\nu))$ was used to determine the activation energy, $\Delta G^{\ddagger}$, from the coalescence temperature, T_c (K), and the frequency of separation of the peaks, $\Delta\nu$ (Hz).

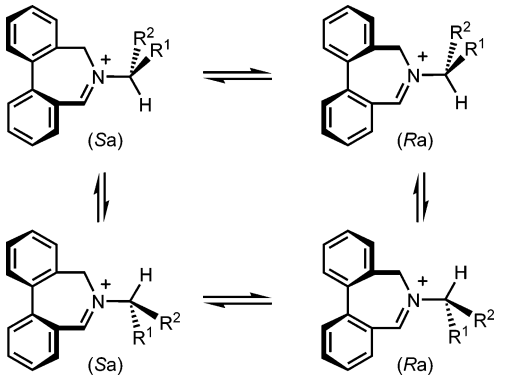


FIGURE 7. Conformations of catalyst **7** as a combination of rotameric and atropisomeric geometries.

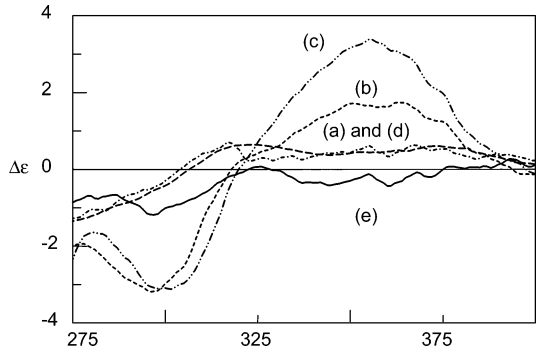


FIGURE 8. CD spectra of (a) [**7a**][**9**] (– – –), (b) [**7b**][**9**] (- - -), (c) [**7c**][**9**] (– · · –), (d) [**7d**][**9**] (- · -), and (e) [**7e**][**9**] (straight line) in CH_2Cl_2 (10^{-5} M, 20 °C).

measured for the derivatives of amines **a**, **b**, and **c**, respectively; the structures derived from amines **a** and **b** displayed the slowest motions.[40] In view of these results, it is likely that such hindered rotation around the N(sp^2)–C(sp^3) bond also occurs for salts [**7a**][**9**] and [**7b**][**9**], leading to a maximum of four atropisomers (Figure 7). Because it is improbable that the barrier of interconversion between the biaryl atropisomers changes upon a modification of the exocyclic appendage, the two signals observed at 298 K must correspond to rotamers with 52:48 and 60:40 ratios in the case of salts [**7a**][**9**]and [**7b**][**9**], respectively. For salt [**7b**][**9**], as the sample is cooled to 233 K, one of the signals is split and the ratio between the (*R*a) and (*S*a) conformers reaches a 67:33 value.[41] The analysis of the signals of salt [**7a**][**9**] could not be pursued due to the "disappearance" of one of the signals at 233 K caused, most probably, by a very large difference of the chemical shifts of the diastereomeric iminium proton signals at low temperature. The selectivity ratios and excesses measured in these NMR experiments are summarized in Table 5.

Conformational studies of biphenyl moieties can also be performed by CD, as the predominance of one equilibrating atropisomer leads to the appearance of Cotton effects in the UV region. The positive or negative nature of the bands depends on the configuration of the biaryl moiety.[42] For series of compounds with the same interring angle, the intensity of the Cotton effect is proportional to the enantiomeric or diastereomeric excesses in solution. For salts [**7a**][**9**] to [**7e**][**9**], the presence of the conjugated iminium moiety extends the absorbance of the cations to the 300–400-nm region in which the chiral exocyclic appendages are CD silent. The use of racemic TRISPHAT also ensures a lack of participation of tetrachlorocatecholate chromophores. The spectra of salts [**7a**][**9**] to [**7e**][**9**] are reported in Figure 8.

To our surprise, only compounds [**7c**][**9**] and [**7b**][**9**] displayed measurable negative and positive Cotton effects at 300 and 350 nm, respectively (10^{-5} M, CH_2Cl_2, 20 °C). This was unexpected in view of the NMR results for which low diastereomeric excesses were observed for the other samples (with the exception of [**7a**][**9**]). Only a concentration dependence of the stereoselective induction can be invoked to explain these results because the NMR samples were measured in quite higher concentration (10^{-3} M) than the CD samples. Because good biaryl twisting was expected for the more effective catalysts [**7b**][**9**] and [**7c**][**9**], the lack of induction for compound [**7a**][**9**] is surprising.

In conclusion, no direct or obvious correlation was found between the enantioselectivity of the epoxidation reactions and a stereocontrol of the twisted biaryl bond of the seven-membered ring by exocyclic chiral appendages. Catalysts of type **7** exist as complex mixtures of biaryl (*R*a) and (*S*a) atropisomers and rotamers around the N(sp^2)–C(sp^3) bond. Most probably, the barriers of interconversion between these conformers have low energies in comparison with the transition-state energies leading to oxaziridinium intermediates or epoxide products. The reaction mechanism most probably follows the Curtin–Hammet principle and, as shown, a conformational analysis of the initial catalysts yields little information for the understanding of the selectivity.

However, the results have also shown that (*S*)-1,2,2-trimethylpropylamine derived iminium catalyst **7b** can be essentially as efficient as derivative **7a**. As this bulky amine is commercially available in both enantiomeric forms, which is not the case for acetonamine, its use in the formation of **7b** seems to be an interesting development in this iminium catalyzed chemistry. Furthermore,

(38) Uncuta, C.; Paun, I.; Deleanu, C.; Plaveti, M.; Balaban, A. T.; Roussel, C. *New J. Chem.* **1997**, *21*, 1055–1065. Balaban, T. S.; Gheorghiu, M. D.; Roussel, C.; Balaban, A. T. *Z. Naturforsch.* **1985**, *40B*, 1555–1557. Balaban, A. T.; Gheorghiu, M. D.; Balaban, T. S. *J. Mol. Struct.* **1984**, *114*, 363–366. Balaban, A. T.; Dinculescu, A. *Tetrahedron* **1984**, *40*, 2547–2553. Seeman, J. I.; Schug, J. C.; Viers, J. W. *J. Org. Chem.* **1983**, *48*, 2399–2407. Katritzky, A. R.; Vassilatos, S. N.; Alajarin Ceron, M. *Org. Magn. Reson.* **1983**, *21*, 587–595. Seeman, J. I.; Galzerano, R.; Curtis, K.; Schug, J. C.; Viers, J. W. *J. Am. Chem. Soc.* **1981**, *103*, 5982–5984. Balaban, A. T.; Uncuta, C.; Dinculescu, A.; Elian, M.; Chiraleu, F. *Tetrahedron Lett.* **1980**, *21*, 1553–1556.

(39) Laleu, B.; Herse, C.; Laursen, B. W.; Bernardinelli, G.; Lacour, J. *J. Org. Chem.* **2003**, *68*, 6304–6308.

(40) Although the NMR behavior of the acridinium salt derived from amine **d** was not studied, one can estimate its rotation barrier is in the range of 12 kcal/mol^{-1}; a value that has been determined for the (1)-phenylpropan-1-amine. See ref 39.

(41) The other signal only sharpens as the temperature is decreased. For this rotamer, it seems that the signals of the iminium proton of the (*R*a) and (*S*a) conformers are isochronous.

(42) An empirical rule formulated by Mislow and co-workers states that nonconjugated bridged biphenyls with a (*S*) configuration (*P* helicity) and an inter-ring angle of ca. 45° will have a negative Cotton effect centered at 240–250 nm: Mislow, K.; Glass, M. A. W.; O'Brien, R. E.; Rutkin, P.; Steinberg, D. H.; Weiss, J.; Djerassi, C. *J. Am. Chem. Soc.* **1962**, *84*, 1455. Its predictability was later confirmed by Sandström: Borecka, B.; Cameron, T. S.; Linden, A.; Rashidy-Ranjbar, P.; Sandström, J. *J. Am. Chem. Soc.* **1990**, *112*, 1185.

temperature experiments have shown that a decrease of only 20 °C can have a positive impact on enantiomeric excesses.

Experimental Section

General Procedure for the Synthesis of Azepines 11a to 11e. To a solution of biphenyl-2,2′-dicarboxaldehyde **10** (1.0 equiv)[29] in CH_3CN (6 mL per 0.1 g of dicarboxaldehyde) was added the corresponding enantiopure amine, **a**−**e** (2.0 equiv). After 15 min of stirring, $NaBH_3CN$ (2.0 equiv) was added, and the reaction was stirred for 20 h before the addition of AcOH (∼5 equiv). After 1 h, the reaction mixture was diluted with 2% MeOH/CH_2Cl_2 (30 mL), washed with 1 M NaOH (until pH > 10), dried over Na_2SO_4, and concentrated under reduced pressure. The compound was obtained after purification over silica gel or basic alumina.

6-*N*-((4*S*,5*S*)-2,2-Dimethyl-4-phenyl-1,3-dioxan-5-yl)-5*H*-dibenz[*c*,*e*]azepine (11a). Starting from 1.0 g of **10**, compound **11a** was obtained as a white solid (714 mg, 77%) after chromatography over silica gel using *c*-Hex/EtOAc 4:1 as eluent: $R_f = 0.3$ (SiO_2, *c*-Hex/EtOAc 4:1); mp 115−120 °C; $[\alpha]_D^{20}$ +95.5 (*c* 0.6, EtOH); IR (neat) 2856, 1450, 1257, 1073, 750 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.40 (m, 13H), 5.25 (d, $J = 3.3$ Hz, 1H), 4.29 (d, $J = 2.8$ Hz, 2H), 3.72 (d, $J = 12.5$ Hz, 2H), 3.54 (d, $J = 12.5$ Hz, 2H), 3.00 (s, 1H), 1.63 (s, 3H), 1.62 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.0 (C^{IV}), 140.2 (C^{IV}), 136.7 (C^{IV}), 129.4 (CH), 127.9 (CH), 127.8 (CH), 127.4 (CH), 126.8 (CH), 126.3 (CH), 99.1 (C^{IV}), 74.8 (CH), 62.2 (CH_2), 60.9 (CH), 54.0 (CH_2), 29.5 (CH_3), 30.0 (CH_2), 19.0 (CH_3); MS−EI *m/z* (relative intensity) 385 (1%), 179 (100%); HRMS calcd for $C_{26}H_{27}NO_2$ 385.20418 (100%), found 385.20040.

6-*N*-((*S*)-1,2,2-Trimethylpropyl)-5*H*-dibenz[*c*,*e*]azepine (11b). Starting from 250 mg of **10**, compound **11b** was obtained as a colorless oil (266 mg, 80%) after chromatography over basic alumina using *c*-Hex as eluent: $R_f = 0.6$ (Al_2O_3 basic, *c*-Hex); $[\alpha]^{20}_D$ +38.7 (*c* 0.1, MeOH); IR (neat) 3064, 3017, 2950, 2866, 1481, 1450, 1356, 1096, 751, 609 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.5−7.4 (m, 8H), 3.60 (CH_2N, 2H), 2.67 (q, CHN, $J = 7.1$ Hz, 1H), 1.15 (d, CH_3, $J = 7.1$ Hz, 3H), 1.03 (s, *t*-Bu, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.0 (C^{IV}), 137.1 (C^{IV}), 129.8 (CH), 127.8 (CH), 127.4 (CH), 127.4 (CH), 68.7 (CHN), 54.7 (CH_2N), 36.8 (C^{IV}), 27.1 (CH_3), 11.6 (CH_3); MS−EI *m/z* (relative intensity) 222 (100%), 279 (1%); HRMS calcd for $C_{20}H_{26}N^+$ ($[M + H]^+$) 280.2060, found 280.2043.

6-*N*-((*S*)-*trans*-2-Phenylmethoxycyclohexyl)-5*H*-Dibenz[*c*,*e*]azepine (11c). Starting from 250 mg of **10**, compound **11c** was obtained as a colorless oil (377 mg, 83%) after chromatography over basic alumina using *c*-Hex then *c*-Hex/AcOEt (90:10) as eluent: $R_f = 0.4$ (Al_2O_3 basic, *c*-Hex/EtOAc 9:1); $[\alpha]^{20}_D$ +43.3 (*c* 0.1, MeOH); IR (neat) 3062, 3027, 2928, 2856, 1450, 1084, 748, 697 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.6−7.3 (m, 8H), 4.69 (CHO, 1H), 3.75 (2 × CH_2N and CH−O, 5H), 2.91 (m, CHN, 1H), 2.29 (m, CH, 1H), 2.02 (m, CH, 1H), 1.82 (m, CH_2, 2H), 1.67−1.32 (m, 2 × CH_2, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.2 (C^{IV}), 139.3 (C^{IV}), 136.7 (C^{IV}), 129.9 (CH), 128.3 (CH), 128.0 (CH), 127.9 (CH), 127.7 (CH), 127.6 (CH), 127.3 (CH), 78.2 (CH), 71.0 (CH_2), 67.4 (CH), 52.7 (CH_2), 30.9 (CH_2), 28.1 (CH_2), 24.7 (CH_2), 24.1 (CH_2); MS−ES (+) *m/z* (relative intensity) 382.3 (100%), 284.2 (24%); HRMS calcd for $C_{27}H_{30}NO^+$ ($[M + H]^+$) 384.2322, found 384.2311.

6-*N*-(*S*-1-Phenylpropyl)-5*H*-dibenz[*c*,*e*]azepine (11d). Starting from 250 mg of **10**, compound **11d** was obtained as a colorless oil (260 mg, 70%) after chromatography over silica gel using *c*-Hex/EtOAc 9:1 as eluent: $R_f = 0.4$ (SiO_2, *c*-Hex/EtOAc 4:1); $[\alpha]^{20}_D$ −49.0 (*c* 0.1, MeOH); IR (neat) 3061, 3023, 2969, 2791, 1451, 1023, 748, 701 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.53−7.29 (m, 13H), 3.58 (Ar−CH_2−N, $J = 12.4$ Hz, 2H), 3.29 (Ar−CH_2−N, $J = 12.4$ Hz, 2H), 3.42 (dd, CH−N, $J = 9.6$ and 3.8 Hz, 1H), 2.14−2.07 (m, CH, 1H), 1.81−1.73 (m, CH_2, 1H), 0.69 (t, CH_3, $J = 7.3$ Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.4 (C^{IV}), 141.3 (C^{IV}), 135.3 (C^{IV}), 129.9 (CH), 128.8 (CH), 128.4 (CH), 127.9 (CH), 127.6 (CH), 127.4 (CH), 127.0 (CH), 69.0 (CH−N), 53.2 (NCH_2), 27.3 (CH_2), 10.4 (CH_2); HRMS calcd for $C_{23}H_{24}N^+$ ($[M + H]^+$) 314.1903, found 314.1887.

6-*N*-((*S*)-1-(2-Naphthyl)ethyl)-5*H*-dibenz[*c*,*e*]azepine (11e). Starting from 500 mg of **10**, compound **11e** was obtained as a pale yellow solid (650 mg, 77%) after chromatography over basic alumina using *c*-Hex then *c*-Hex/EtOAc 9:1 as eluents: $R_f = 0.6$ (SiO_2, *c*-Hex/EtOAc 9:1); mp 80−85 °C; $[\alpha]^{20}_D$ −72.0 (*c* 0.1, CH_2Cl_2); IR (neat) 3056, 2971, 2795, 1600, 1506, 1480, 1450, 1366, 1301, 1266, 1218, 1192, 1175, 1144, 1122, 1090, 1069, 1018, 1008, 942, 922, 894, 857, 821, 779, 746 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.09−8.04 (m, 4H), 7.92−7.90 (m, 1H), 7.71−7.60 (m, 6H), 7.58−7.51 (m, 4H), 4.00 (q, CHN, $J = 6.6$ Hz, 1H), 3.80 (d, $J = 12.4$ Hz, 2H), 3.58 (d, $J = 12.6$ Hz, 2H), 1.75 (d, CH_3, $J = 6.6$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.9 (C^{IV}), 141.5 (C^{IV}), 135.4 (C^{IV}), 133.9 (C^{IV}), 133.1 (C^{IV}), 130.01 (CH), 128.7 (CH), 128.1 (CH), 128.0 (CH), 127.9 (CH), 127.8 (CH), 127.7 (CH), 126.1 (CH), 125.8 (CH), 62.8 (CH), 53.4 (CH_2), 22.9 (CH_3); MS−ES (+) *m/z* (relative intensity) 350.3 (100%), 197.5 (62%), 139.7 (70%); HRMS calcd for $C_{26}H_{24}N^+$ ($[M + H]^+$) 350.1903, found 350.1904.

Racemic Diethylammonium TRISPHAT Salt or [H_2NEt_2][9]. Under a nitrogen atmosphere, in a flame-dried 250 mL two-necked round-bottomed flask equipped with a magnetic stirring bar, an addition funnel for solids, and a reflux condenser (topped with a gas outlet connected to a concentrated NaOH trap), 6.0 g of tetrachlorocatechol (crystallized and sublimed) (24.2 mmol, 3 equiv) was added portionwise as a solid over a 30 min period to a 50 °C solution of 1.68 g of PCl_5 (8.1 mmol, 1 equiv) in toluene (20 mL) (HCl_g evolution). Dry toluene (20 mL) was further added to wash the glassware. After 14 h of stirring at 70 °C, the reaction was cooled to room temperature (precipitation) and concentrated in vacuo. The resulting gray powder was suspended in CH_2Cl_2 (43 mL). A solution of diethylamine (8.1 mmol, 1 equiv) in CH_2Cl_2 (17 mL) was then slowly added, leading to the precipitation of a white solid. After 12 h of stirring at 25 °C to ensure maximum precipitation, reaction was filtered over a Büchner funnel. The solid was washed with CH_2Cl_2 and dried under reduced pressure to afford the desired ammonium TRISPHAT salt (5.72 g, 86%): mp 220 °C (decomposition); ^1H NMR (400 MHz, DMSO-d_6) δ 8.16 (br, NH_2, 2H), 2.92 (q, NCH_2, $J = 7.1$ Hz, 4H), 1.16 (t, Me, $J = 7.1$ Hz, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 141.6 (C^{IV}, $J_{CP} = 6.6$ Hz), 122.6 (C^{IV}), 113.6 (C^{IV}, $J_{CP} = 19.8$ Hz), 41.8 (CH_2), 11.5 (CH_3); ^{31}P NMR (162 MHz, DMSO-d_6) δ −80.83; MS−ES (−) *m/z* (relative intensity) 768.5. Anal. Calcd for $C_{22}H_{12}Cl_{12}NO_6P \cdot 0.1C_5H_{12}$: C, 31.79; H, 1.57. Found: C, 31.82; H, 1.70.

General Procedure for the Synthesis of the Iminium TRISPHAT Salts [7a][9] to [7e][9]. To a solution of azepines **11a**−**e** (1 equiv) in CCl_4 (3 mL/1 mmol of substrate) was added NBS (1.3 equiv) and AIBN (0.05 equiv) as solids. The flask was protected with an aluminum foil. The mixture was stirred overnight. The reaction was diluted with water (15 mL/1 mmol of substrate) and extracted with CH_2Cl_2 (2 × 10 mL). The organic phase was dried ($MgSO_4$) and filtered. A solution of salt [Me_2NH_2][**9**] (1.2 equiv) in acetone was added, and the crude evaporated under reduced pressure. Salts [**7a**][**9**] to [**7e**][**9**] were then isolated by chromatography over silica gel or basic alumina.

[6-*N*-((4*S*,5*S*)-2,2-Dimethyl-4-phenyl-1,3-dioxan-5-yl)-5*H*-dibenz[*c*,*e*]azepinium][9] or [7a][9]. Starting from 250 mg of **11a**, salt [**7a**][**9**] was obtained as a pale yellow solid (456 mg, 61%) after chromatography over silica gel using CH_2Cl_2 as eluent: $R_f = 0.3$ (SiO_2, CH_2Cl_2); mp 200 °C (decomposition); $[\alpha]^{20}_D$ +28.0 (*c* 0.1, CH_2Cl_2); IR (neat) 1625, 1581, 1537 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 9.34−8.83 (br, CH=N, 2H), 7.87−7.17 (m, 13H), 5.87 (s, CH−Ar, 1H), 5.34−4.00 (m, CH_2−N and CHN and CH_2−O, 5H), 1.86 (s, CH_3, 3H), 1.77 (s, CH_3, 3H); ^{31}P NMR (162 MHz, $CDCl_3$) δ −80.9, −80.80; MS−ES (−) *m/z* (relative intensity) 769.0 (44%, TRISPHAT), 113.7 (100%); MS−ES (+) *m/z* (relative intensity) 152.7 (100%), 384.4 (16%,

M); CD (CH_2Cl_2, 10^{-5} M) λ ($\Delta\epsilon$) 244 (8.6), 265 (−1.5), 320 (0.8); UV (CH_2Cl_2, 10^{-5} M) λ (log ϵ) 237 (4.82), 300 (4.41), 356 (3.95). Anal. Calcd for $C_{44}H_{26}Cl_{12}NO_8P\cdot H_2O$: C, 45.13; H, 2.41. Found: C, 44.75; H, 2.47.[43]

[6-*N*-((*S*)-1,2,2-Trimethylpropyl)-5*H*-dibenz[*c,e*]azepinium][9] or [7b][9]. Starting from 250 mg of **11b**, salt [**7b**][**9**] was obtained as a pale yellow solid (544 mg, 58%) after chromatography over basic alumina with CH_2Cl_2 as eluent: R_f = 0.9 (Al_2O_3 basic, CH_2Cl_2); mp 160 °C (decomposition); $[\alpha]^{20}_D$ −31.2 (*c* 0.1, CH_2Cl_2); IR (neat) 2923, 1636, 1597, 1556, 1445, 1389, 1302, 1236, 1091, 1046, 1008, 989, 818, 760, 718, 668 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.49 and 9.20 (2s, CH=N, 1H), 8.1−7.0 (m, 8H), 4.82−4.33 (m, CH_2−N and CHN, 3H), 1.75 (m, CH_3, 3H), 1.19 (s, *t*-Bu, 9H); ^{31}P NMR (162 MHz, $CDCl_3$) δ −80.92, −81.00; MS−ES (−) *m/z* (relative intensity) 768.5 (100%, TRISPHAT); MS−ES (+) *m/z* (relative intensity) 194.5 (100%, M − C_6H_{13}), 278.5 (25%, M); CD (CH_2Cl_2, 10^{-5} M) λ ($\Delta\epsilon$) 252 (−6), 277 (−2), 296 (−3), 351 (2); UV (CH_2Cl_2, 10^{-5} M) λ (log ϵ) 227 (4.75), 239 (4.70), 301 (4.27), 356 (3.49). Anal. Calcd for $C_{38}H_{24}Cl_{12}NO_6P$: C, 43.59; H, 2.31. Found: C, 43.47; H, 2.51.[43]

[6-*N*-((*S*)-*trans*-2-Phenylmethoxycyclohexyl)-5*H*-dibenz[*c,e*]azepinium][9] or [7c][9]. Starting from 350 mg of **11c**, salt [**7c**][**9**] was obtained as a pale yellow solid (526 mg, 50%) after chromatography over basic alumina with CH_2Cl_2 as eluent: R_f = 0.9 (Al_2O_3 basic, CH_2Cl_2); mp 185 °C (decomposition); $[\alpha]^{20}_D$ −8.0 (*c* 0.1, CH_2Cl_2); IR (neat) 2935, 1707, 1641, 1597, 1556, 1446, 1389, 1302, 1236, 1074, 990, 819, 759, 718, 668 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.95 (s, CH=N, 1H), 7.97−7.45 (m, 8H), 7.19−6.89 (m, 5H), 4.44−3.67 (m, 6H), 2.49 (br, 1H), 2.12 (br, 1H), 1.93 (br, 3H), 1.39 (br, 3H);^{31}P NMR (162 MHz, $CDCl_3$) δ −80.83, −80.87; MS−ES (−) *m/z* (relative intensity) 768.5 (100%, TRISPHAT); MS−ES (+) *m/z* (relative intensity) 382.4 (100%, M); CD (CH_2Cl_2, 10^{-5} M) λ ($\Delta\epsilon$) 252 (−11), 282 (−2), 300 (−3), 357 (4); UV (CH_2Cl_2, 10^{-5} M) λ (log ϵ) 227 (4.79), 240 (4.75), 300 (4.35), 351 (3.55). Anal. Calcd for $C_{45}H_{28}Cl_{12}NO_6P$: C, 46.95; H, 2.45. Found: C, 47.22; H, 2.73.[43]

[6-*N*-((*S*)-1-Phenylpropyl)-5*H*-dibenz[*c,e*]azepinium][9] or [7d][9]. Starting from 250 mg of **11d**, salt [**7d**][**9**] was obtained as a pale yellow solid (552 mg, 64%) after chromatography over basic alumina with CH_2Cl_2 as eluent: R_f = 0.9 (Al_2O_3 basic, CH_2Cl_2); mp 195 °C (decomposition); $[\alpha]^{20}_D$ −31.7 (*c* 0.1, CH_2Cl_2); IR (neat) 1640, 1598, 1556, 1445, 1389, 1301, 1236, 990, 819, 758, 718, 700, 668 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 9.86 (br, CHN, 1H), 7.85−7.06 (m, 13H), 5.61 (m, NCH, 1H), 4.75 (m, CHN, 1H), 4.19 (m, NCH, 1H), 2.38 (m, CH_2, 2H), 1.13−0.69 (br, CH_3, 3H);^{31}P NMR (162 MHz, $CDCl_3$) δ −80.97, −81.01; MS−ES (−) *m/z* (relative intensity) 768.5 (100%, TRISPHAT); MS−ES (+) *m/z* (relative intensity) 194.5 (70%, M−C_9H_{11}), 312.3 (100%, M); CD (CH_2Cl_2, 10^{-5} M) λ ($\Delta\epsilon$) 237 (−3); UV (CH_2Cl_2, 10^{-5} M) λ (log ϵ) 227 (4.795), 240 (4.74), 301 (4.34), 363 (3.50). Anal. Calcd for $C_{41}H_{22}Cl_{12}NO_6P$: C, 45.55; H, 2.05. Found: C, 45.38; H, 2.25.[43]

[6-*N*-((*S*)-1-(2-Naphthyl)ethyl)-5*H*-dibenz[*c,e*]azepinium][9] or [7e][9]. Starting from 627 mg of **11e**, salt [**7e**][**9**] was obtained as a pale yellow solid (1.31 g, 66%) after chromatography over basic alumina with CH_2Cl_2 as eluent: R_f = 0.9 (Al_2O_3 basic, CH_2Cl_2); mp 220 °C (decomposition); $[\alpha]^{20}_D$ −28.2 (*c* 0.1, CH_2Cl_2); IR (neat) 1641, 1597, 1556, 1444, 1389, 1301, 1236, 1008, 989, 819, 718, 668 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$, 298 K) δ 2.27 (br, Me, 3H), 4.38 (br, N−CH, 1H), 4.88 (br, CHN, 1H), 6.13 (br, CHN, 1H), 6.55 (br, 1H), 7.08 (br, 1H), 7.25−7.95 (m, 11H), 8.26 (s, 1H), 9.95 (br, N=CH, 1H); ^{31}P NMR (162 MHz, $CDCl_3$) −80.97, −81.01; MS−ES (−) *m/z* (relative intensity) 768.5 (100%, TRISPHAT); MS−ES (+) *m/z* (relative intensity) 348.3 (55%), 194.5 (100%), 155.6 (100%); CD (CH_2Cl_2, 10^{-5} M) λ ($\Delta\epsilon$) 235 (−9); UV (CH_2Cl_2, 10^{-5} M) λ (log ϵ) 229 (5.08), 301 (4.36). Anal. Calcd for $C_{44}H_{22}Cl_{12}NO_6P$: C, 47.31; H, 1.99. Found: C, 47.51; H, 2.21.[43]

Biphasic Asymmetric Epoxidation Procedure. In a 10 mL flask equipped with a magnetic stirring bar, $NaHCO_3$ (67.0 mg, 0.80 mmol, 4.0 equiv) was added to 800 μL of water. Oxone (132.0 mg, 0.21 mmol, 1.0 equiv) was then added, and the solution was stirred for 2 min until effervescence subsided. A 400-μL portion of a 0.5 mol/L solution of the alkene (0.20 mmol, 1.0 equiv) and naphthalene/dodecane (0.20 mmol, 1.0 equiv, internal reference) in CH_2Cl_2 was added. The catalyst (10.0 μmol, 5 mol %) in CH_2Cl_2 (600 μL) was added, followed by a solution of 18-crown-6 (1.0 mg, 5.0 μmol, 2.5 mol %) in CH_2Cl_2 (200 μL). The reaction mixture was then stirred at room temperature for 2 h.

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Supporting Information Available: ^{1}H NMR, VT-NMR, and CD spectra of compounds [**7a**][**9**] to [**7e**][**9**]; collective spectral data (^{1}H and ^{13}C NMR) of salt [Et_2NH_2][**9**]; and compounds **11a**−**e**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(43) Assignment in ^{13}C NMR spectroscopy could not be performed due to the low resolution of the spectra resulting from the slow interconversion of the biphenyl moiety on the NMR time scale, leading to a broadening of the NMR signals.