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Synthesis, Functionalization, and Optical Properties of Chiral Carbazole-Based Diaza[6]helicenes

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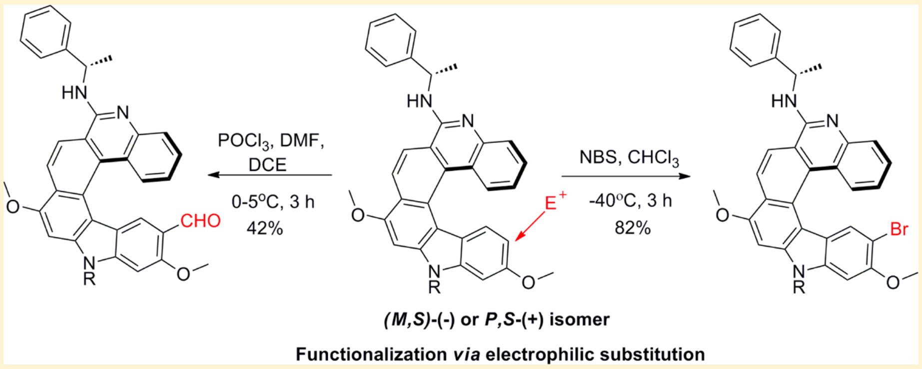
Supporting Information



ABSTRACT: In the present study, carbazole-based diaza[6]helicenes were synthesized utilizing versatile quinoline and 9-(2-ethylhexyl)-2,7-dimethoxycarbazole-3-carbaldehyde building blocks via the Wittig reaction−photocyclization strategy. The presence of bifunctional units comprising electrophilic chloroquinoline and electron-rich carbazole has opened up new opportunities. The chloro group was substituted with a chiral amine, allowing diastereomeric separation, and the chiral forms were monofunctionalized via electrophilic substitution on the carbazole unit. Postcyclization functionalization via substituting the carbazole unit provides a platform for the synthesis of chiral functionalized materials with potential application in fields such as asymmetric synthesis and organic electronics. The configuration of the diaza[6]helicene diastereomers was demonstrated by time-dependent density functional theory (TD-DFT) calculations. Furthermore, on the basis of the DFT calculations of the HOMO−LUMO energy levels of the chiral forms, these compounds can be potentially of interest as hole-transporting compounds

INTRODUCTION

Helicenes belong to an interesting class of polycyclic aromatic or heteroaromatic compounds with ortho-annulated rings. These unique and extended aromatic systems are well-known for their inherent chirality.[1] The system cannot remain planar as the number of ortho-annulated rings increases, and it releases the steric strain by adopting either the *P* or *M* configuration.[2] These unique three-dimensional aromatic systems are thermally stable and have attracted an ever-increasing amount of attention, and their chemistry has been considerably enriched owing to their interesting optical and electronic properties.[3]

Helicenes, with heteroaromatic units incorporated in the π systems, have been extensively studied due to their interesting self-assembly in the solid state,[4] their ability to behave as organic semiconductors,[5] and their use in optical resolution.[6] Furthermore, potential applications of the enantiomerically pure, functionalized derivatives of (hetera)helicenes can be realized because they are configurationally stable and form supramolecular architectures that exhibit second-order nonlinear optical and chiro-optical properties.[3]

The last decade highlighted carbohelicenes[7a−c] as helical-dominating frameworks, but heterahelicenes,[7d] for example, aza- and thiahelicene, have also emerged as a very attractive class of molecules. The ambiguities associated with an all-benzene helix can be removed by the introduction of a hetereoaromatic unit. Azahelicenes belongs to a subgroup of heterahelicenes, with possible applications in fields such as light-emitting devices and chemosensors.[7e,f] Azahelicene derivatives have also been reported to have applications in enantioselective transformations, as chiral inducers, in the fields of asymmetric catalysis,[8] self-assembly,[9] and metal coordination complexes.[10]

Classical photochemical cyclization has been described by Caronna et al.[11] and is one of the most utilized methods for the

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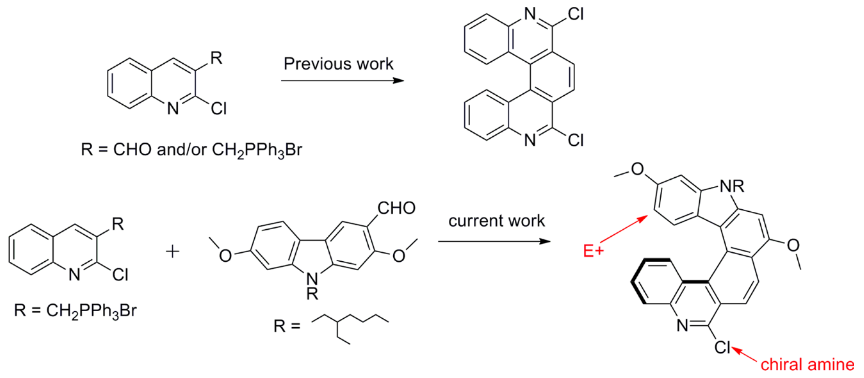
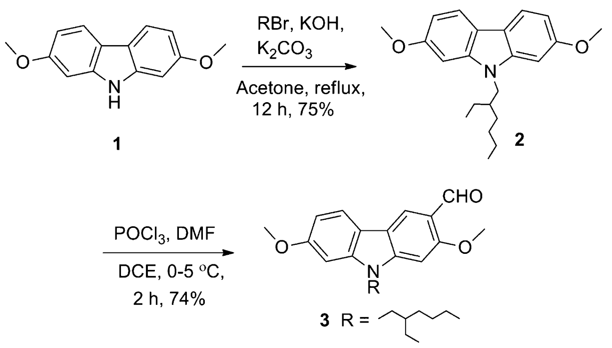
Scheme 1. Overview of Previous and Current Work



Scheme 2. Synthesis of 9-(2-Ethylhexyl)-2,7-dimethoxycarbazole-3-carbaldehyde 3



synthesis of azahelicenes. A versatile synthetic method was described by Harrowven and co-workers[12] based on Bu_3SnH-mediated coupling. Furthermore, metal-catalyzed cyclizations[12c] include the [2 + 2 + 2] cycloisomerization of triynes[12b] and palladium-catalyzed arylations. Recently, Lui et al.[13a] described the synthesis of carbazole-based diaza[7]helicenes and described their application as a deep-blue emitter in an organic light-emitting diode (OLED). This new class of helicenes, with a carbazole framework, could open new possibilities for the utilization of helicene derivatives in OLEDs and could also have potential applications in other organic electronic fields.[13b,c] We envisage that combining the carbazole unit with the readily available quinoline building block previously synthesized by us would result in the formation of a donor−acceptor hybrid system with interesting electronic properties and potential applications in organic electronics. Furthermore, chiral resolution via diastereomeric separation and postcyclization functionalization could be realized with this system, leading to a chiral helical donor−acceptor hybrid system, which is an added advantage over the chiral diaza[5]helicenes previously synthesized by this methodology.

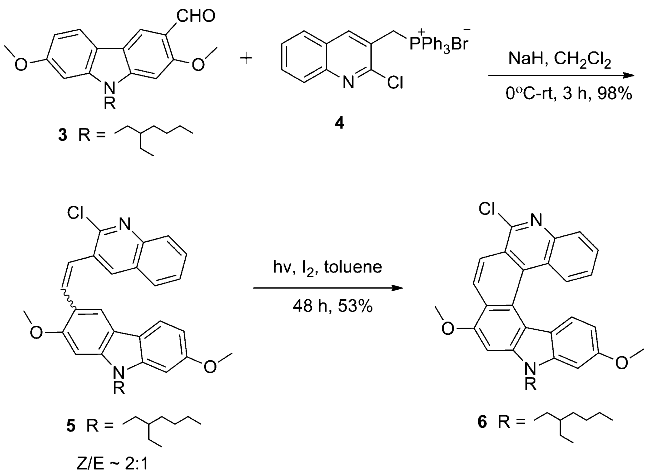
Scheme 1 represents an overview of the past and current work. In our previous work,[14] diversely functionalized diaza[5]-helicenes were synthesized from a quinoline building block utilizing the Wittig reaction and a photochemical cyclization strategy. In the present work, we utilize this quinoline and 9-(2-ethylhexyl)-2,7-dimethoxycarbazole-3-carbaldehyde as building blocks to synthesize carbazole-based helicenes. These bifunctional systems comprising chloroquinoline and carbazole units are useful. The chloro group can be substituted with a chiral amine, leading to diastereomeric separation, and the chiral forms can further be functionalized via electrophilic substitution on the carbazole unit. Postcyclization functionalization via substituting the carbazole unit opens new opportunities for the synthesis of chiral functionalized materials.

■ RESULTS AND DISCUSSION

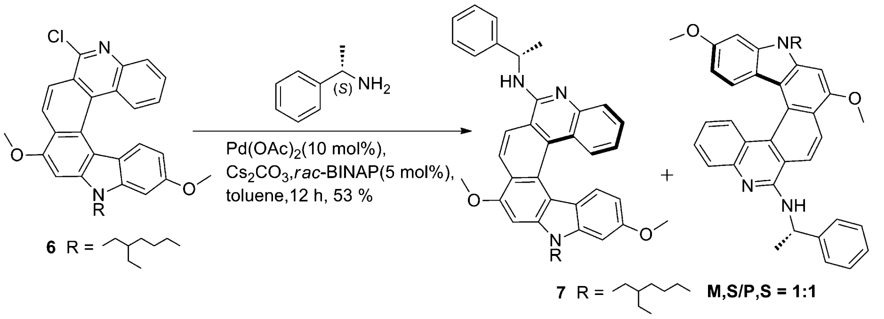
In the present approach, 9-(2-ethylhexyl)-2,7-dimethoxycarbazole-3-carbaldehyde **3** was utilized as one of the building blocks. This building block, **3**, was prepared in two steps from 2,7-dimethoxycarbazole **1**, which was prepared according to earlier reported procedures.[15] Alkylation of compound **1** was done using 2-ethylhexyl bromide according to a literature procedure[16] to obtain alkylated product **2** in 75% yield. Vilsmeier−Haack formylation of compound **2** gave aldehyde **3** in 74% yield (Scheme 2). Wittig olefination of phosphonium salt **4**, prepared according to a literature procedure,[14] and aldehyde **3**, using NaH as base in CH_2Cl_2, gave asymmetric precursor **5** (Z/E ∼ 2:1) in 98% yield. The alkene was obtained with a moderate degree of Z selectivity. Characterization of compound **5** was carried out by ^1H and ^{13}C NMR spectroscopy and HRMS.

The ratio of the isomers was determined by integration of the ^1H NMR spectrum to be Z/E = 2:1. We observed a high ratio of the cis isomer, which is beneficial during the irradiation process as compared to the trans isomer, which shows poor solubility. The obtained precursor **5** was subjected to oxidative photocyclization using iodine and toluene as the solvent (1.0 mM) (Scheme 3).

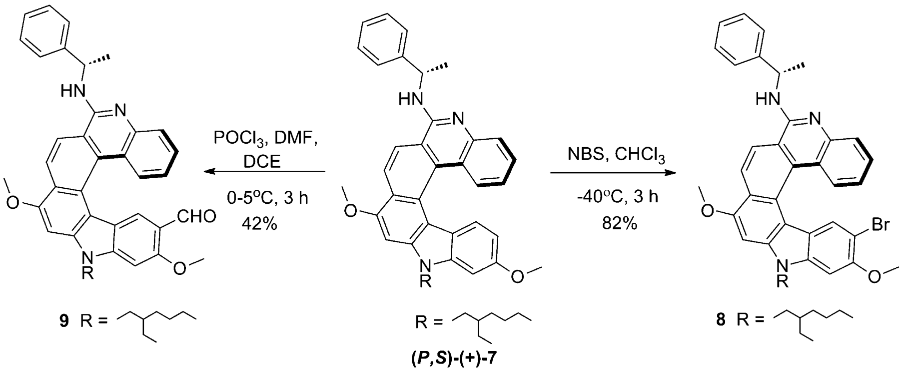
Scheme 3. Synthesis of Carbazole-Based Diaza[6]helicene via Wittig Reaction and Photochemical Cyclization



Scheme 4. Resolution via Diastereomeric Separation



Scheme 5. Functionalization of Chiral Forms via Electrophilic Substitution



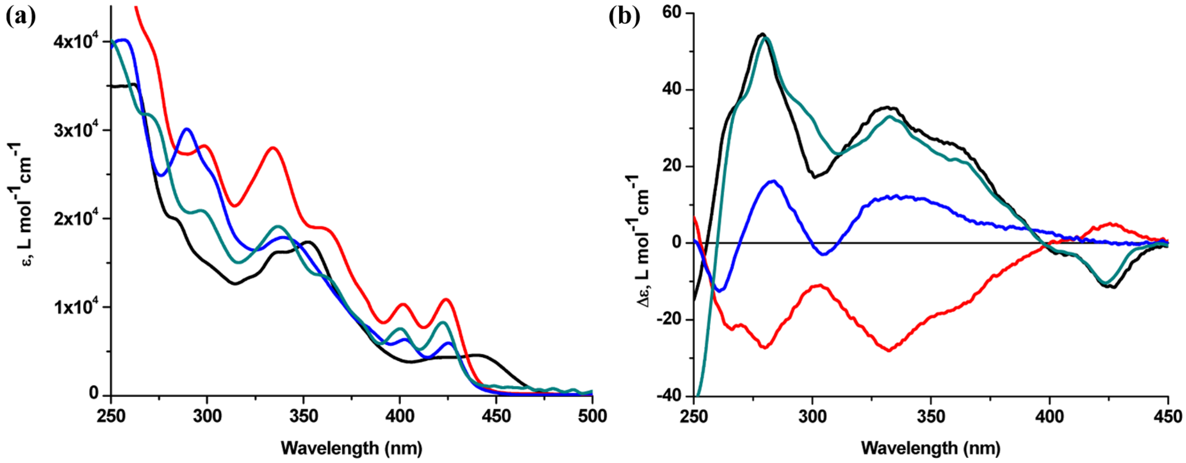


Figure 1. (a) UV−visible spectra of compounds **6** (black), **7** (red), **8** (green), and **9** (blue) in dilute $CHCl_3$ solution (10 μM). (b) CD spectrum of diastereomers (*P*,*S*)-(+)-**7** (black), (*M*,*S*)-(−)-**7** (red), (*P*,*S*)-(+)-**8** (green), and (*P*,*S*)-(+)-**9** (blue) in dilute $CHCl_3$ solution (10 μM).

A Rayonet photochemical reactor with interchangeable light sources (wavelength, 350 nm) was used for the irradiation process to obtain diaza[6]helicene **6** in 53% yield. Compound **6** was characterized by HRMS and NMR spectroscopy.

Resolution via Diastereomeric Separation. On the basis of our previous knowledge of resolution via diastereomeric separation using a chiral amine, the chloro group was substituted utilizing the Buchwald−Hartwig amination reaction.[14] Amination reaction of **6** with *S*-(−)-α-methyl benzylamine using Cs_2CO_3, as the base, 10 mol % $Pd(OAc)_2$, 5 mol % *rac*-BINAP, and toluene as the solvent gave desired product **7** in 53% yield (1:1 mixture of diastereomers) (Scheme 4). The ratio was determined by integrating the ^{1}H NMR spectra.

The obtained diastereomers were readily separated via standard chromatography. The ease of separation of the chiral forms led to better characterization (NMR and CD spectroscopy) and utilization in further functionalization. These diastereomers were configurationally very stable at room temperature. (Qualitative analysis showed that these diastereomers were stable for 12 h at 150 °C; there is no observable racemization after heating the diastereomers at 150 °C for 12 h.)

Functionalization of Chiral Forms via Electrophilic Substitution. Functionalization of the chiral forms of diaza[6]helicene was done by utilizing the carbazole unit. The helicene core was functionalized via electrophilic substitution reactions.

The substitution of diastereomer (*P*,*S*)-(+)-**7** with bromine was done using NBS and $CHCl_3$[17] as the solvent at −40 °C to furnish brominated diaza[6]helicene **8** in 82% yield. In addition

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Table 1. Computational Data of the Selected Transitions and Their Contribution to the CD Spectra of Helicene (*P*,*S*)-(+)-7 (*conf1*) and (*M*,*S*)-(−)-7 (*conf1*) Calculated at the TD-B3LYP/6-31G(d,p)/PCM (Chloroform) Level

comp.	exp. CD, λ, nm ($\Delta\varepsilon$)	calcd. CD λ, nm	transition	oscillator strength	rotatory strength, cgs units	contributions
(*M*,*S*)-7	427 (4.7)	405	1	0.155	50.1	HOMO → LUMO (95%)
	366 (−31)	354	3	0.337	−56.9	HOMO → LUMO + 1 (66%)
	333 (−28)	277	4	0.176	−58.8	HOMO-2 → LUMO (87%)
	280 (−27)	286	8	0.114	−159	HOMO → LUMO + 2 (74%)
(*P*,*S*)-7	427 (−11)	399	1	0.152	−38.3	HOMO → LUMO (91%)
	360 (25)	348	3	0.175	35.6	HOMO → LUMO + 1 (53%)
	332 (35)	275	4	0.248	81.3	HOMO-2 → LUMO (62%)
	298 (54)	280	10	0.032	133	HOMO → LUMO + 2 (32%)

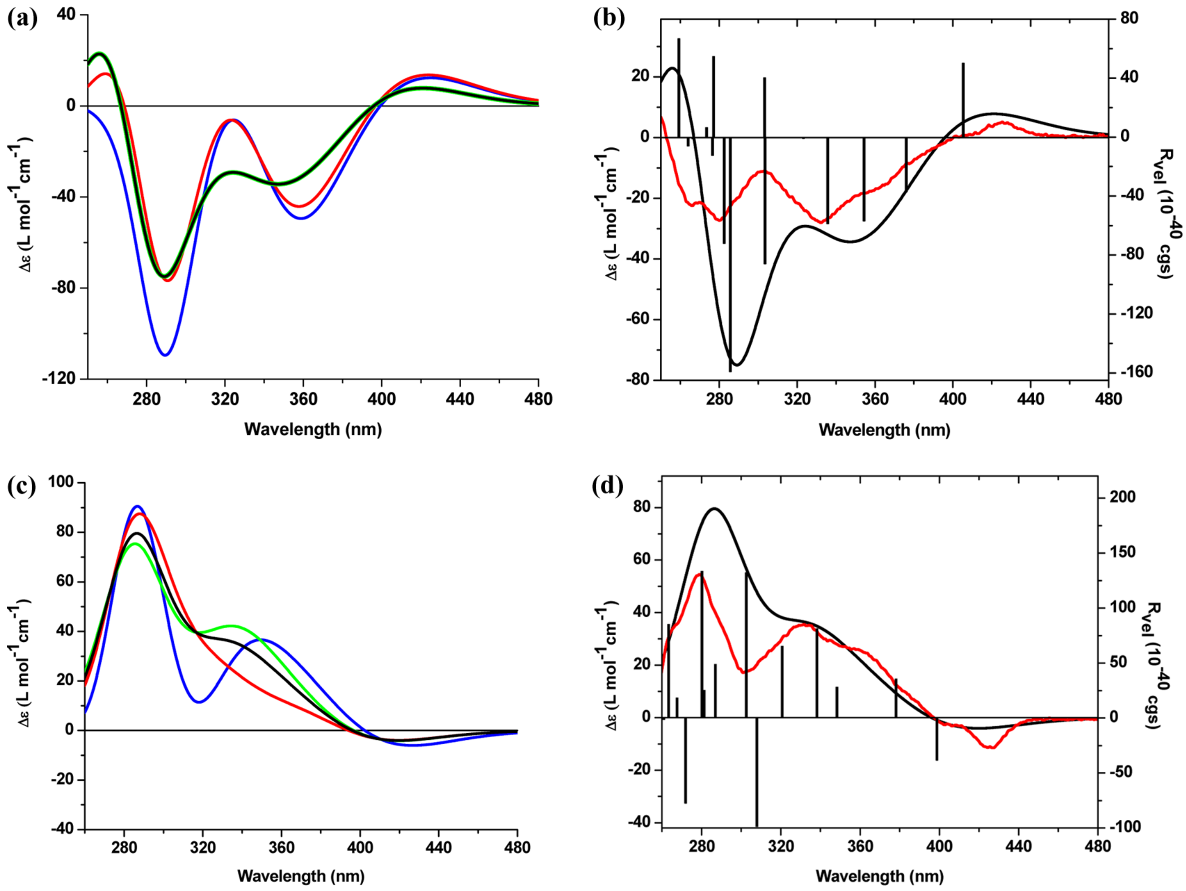
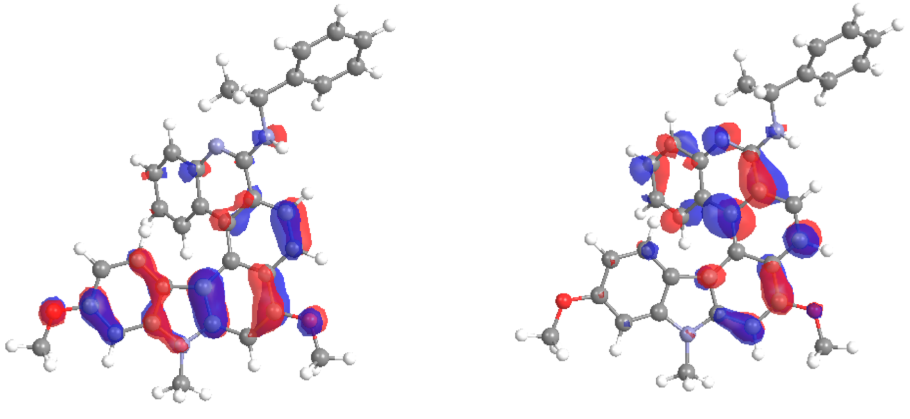


Figure 2. (a) Theoretical CD spectra for individual conformers of diastereomer (*M*,*S*)-7 (*conf1* (green), *conf2* (red), and *conf3* (blue)) and Boltzmann-averaged CD spectra (black). (b) Comparison of the experimental (red) and theoretical (black) CD spectra of most stable conformer of diastereomer (*M*,*S*)-(−)-7 calculated at the TD-B3LYP/6-31G(d,p) level (σ = 0.30 eV) for the Boltzmann-averaged CD spectra of the three most stable conformers (black); bars represent the rotatory strength for the most abundant *conf1*. (c) Theoretical CD spectra for individual conformers of diastereomer (*P*,*S*)-(+)-7 (*conf1* (green), *conf2* (red), and *conf3* (blue)) and Boltzmann-averaged CD spectra (black). (d) Comparison of experimental (red) and theoretical (black) CD spectra of diastereomer (*P*,*S*)-7, calculated at the TD-B3LYP/6-31G(d,p) level (σ = 0.30 eV) for the Boltzmann-averaged CD spectra of the three most stable conformers (black); bars represent the rotatory strength for the most abundant *conf1*.

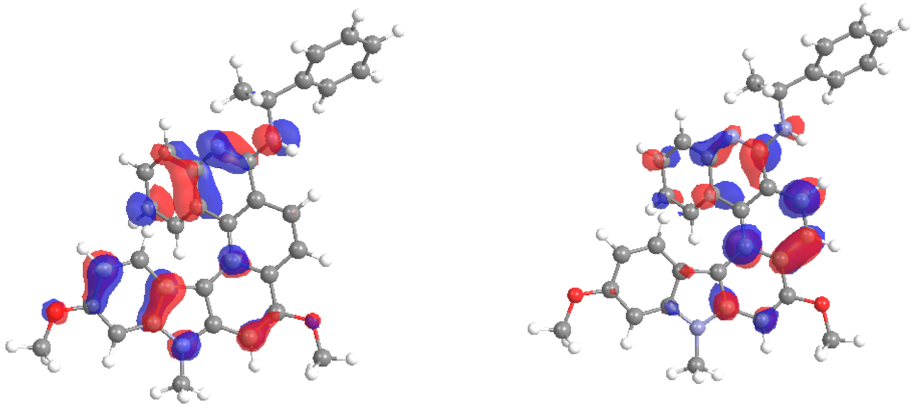
to the references given and to prove the electrophilic substitution reaction position, as depicted in Scheme 5, the electrostatic charges of the (*P*,*S*)-(+)-7 diastereomer were calculated using the B3LYP/6-31G(d,p) method. The observed values at the C-1, C-3, and C-8 positions of the carbazole fragment were found to be −0.429, −0.420, and −0.356, respectively. Although C-1 is slightly (0.009) more electron rich than C-3, the higher reactivity of C-3 could be attributed to lower steric shielding by the methoxy group present at the C-2 position. Vilsmeier−Haack formylation of diastereomer (*P*,*S*)-(+)-7 using DMF and POCl$_3$ gave formyl substituted diaza[6]helicene **9** in 42% yield. The structural identity of the substituted azahelicenes was confirmed by NMR, HRMS, and CD spectroscopy.

UV−Visible and CD Spectroscopy. Absorption spectra for compounds **6**−**9** in dilute CHCl$_3$ solutions are shown in Figure 1a. A hypsochromic shift is observed for compound **7** compared to helicene **6**, which could be a result of substitution of the helicene core with the amine. The spectra of compounds **8** and **9** are comparable to that of **7**.

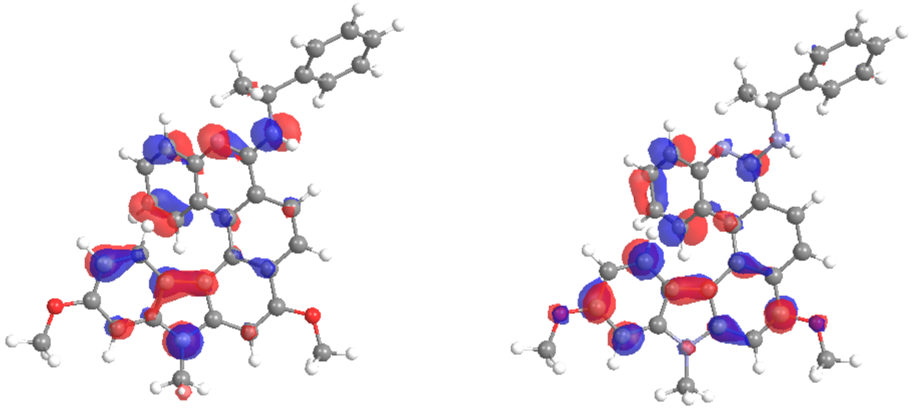
In the CD spectrum of diastereomer (+)-**7**, we observe a small negative peak followed by several large positive bands. As expected, the spectrum of the other diastereomer, (−)-**7**, is the mirror image of this.



HOMO LUMO



HOMO-1 LUMO+1



HOMO-2 LUMO+2

Figure 3. (*M*,*S*)-7 (*conf1*) molecular orbitals (isovalue is 0.040).

On the basis of earlier literature,[18] it is commonly accepted that the sign of the CD *β*-band is representative of the absolute configuration of the helicene, with a positive band corresponding to the P helicity and vice versa. On the basis of this, we can attribute P helicity to diastereomer (+)-7 and M helicity to diastereomer (−)-7.

Theoretical Calculation Related to Diastereomers (*P*,*S*)-(+)-7 and (*M*,*S*)-(−)-7: Calculated CD of (*P*,*S*)-(+)-7 and (*M*,*S*)-(−)-7. CD calculations of the three most stable conformers obtained were performed using time-dependent density functional theory with the B3LYP functional, the 6-31G(d,p) basis set, and PCM in chloroform.[19a,b] The CD spectra of the most populated conformers were calculated and Boltzmann-averaged (Table 1 and Figure 2). In many cases, the conformational equilibrium has an influence on the CD spectra.[19c] The results of the conformational analysis of 7 show changes in the CD spectra ranging between 350 and 370 nm. The shoulders in this range in the experimental CD spectra at 366 and 360 nm for diastereomers (*M*,*S*)-7 and (*P*,*S*)-7 are the effect of different conformers (Figure 3b,d). Excitation energies and oscillator and rotatory strengths for the diastereomers of helicene 7 (*conf1*) are presented in Table 1.

We analyzed the molecular orbitals (MO) of diastereomer (*M*,*S*)-7 because the (*S*)-*α*-methyl benzylamine moiety has no effect on the MO of helicene. For helicene (*M*,*S*)-**7**, the lowest energy and small intensity with a positive Cotton effect (CE) band at 427 nm was influenced by one transition, $S_0 \rightarrow S_1$, at 405 nm. The first excitation with the oscillator strength of 0.155 for (*M*,*S*)-**7** corresponds to the HOMO → LUMO transition. This transition is localized on the helicene moiety and is assigned to the forbidden ^1L_b transition, by Platt's nomenclature.[20] This transition is known to be less useful for the analysis of the CD spectra of helicenes.[21] The bands with strong negative CEs were observed at 277 and 286 nm for (*M*,*S*)-**7**, which are assigned as ^1B_a and ^1B_b transitions, respectively. The signs of these CEs can be readily used as a tool for the estimation of the absolute configuration of helicenes. Clearly visible levorotatory electron density migration was observed from the transition $S_0 \rightarrow S_4$, which corresponds to 87% of the transition HOMO-2 → LUMO. The electron density in the orbital HOMO-2 is located on the carbazole and quinoline parts of helicene. After excitation, the electrons migrate to the quinoline part (LUMO). By comparing and interpreting the theoretical and experimental data, *P* (dextrorotatory) and *M* (levorotatory) helicities were obtained, and significant agreement between the CD characteristics of the helicenes was observed (Figure 2a−d). The main CD bands were predicted with the correct CE, and the positions were found to be comparable with the experimental spectra for both compounds.

Additionally, DFT calculations were performed for helicene **7** to study the HOMO and LUMO electronic distribution. Due to the strong electron-donating property of the carbazole moiety and electron-accepting property of the quinoline species of the helicene, the HOMO of **7** was mainly dispersed over the carbazole moiety, whereas the LUMO was localized on the quinoline part (Figure 3). The HOMO and LUMO energy levels were calculated for helicenes (*M*,*S*)-**7** and (*P*,*S*)-**7** to be −4.95/−1.38 and −5.10/−1.48 eV, respectively. Taking into account their semiconducting properties, these compounds act as electron donors and their HOMO is about −5 eV. Moreover, for electron-transporting n-type organic semiconductors, quite a low LUMO (∼−3.0 eV) is needed.[22] In our case, the LUMO is below −1.5 eV. This observation shows that these compounds can be potentially of interest as hole-transporting p-type semiconductors.

■ CONCLUSIONS

To summarize, we have developed an efficient method for the synthesis of carbazole-based diaza[6]helicenes. The presence of bifunctional units in this strategy provides us with an opportunity to substitute the chloro group of the quinoline unit, leading to the resolution of the racemic helicene and further functionalization of the chiral forms utilizing the carbazole unit. Electrophilic substitution reactions were performed, resulting in the formation of functionalized chiral materials. The bromine and aldehyde groups are ideal starting points for further elaboration. We envisage that the bromine or aldehyde can be further converted to groups suitable for use in catalysis. An efficient synthetic methodology that can be further functionalized with ease provides the chiral forms of diaza[6]helicenes for use in various applications.

■ EXPERIMENTAL SECTION

General Experimental Procedures. NMR spectra were acquired on commercial instruments (300 and 600 MHz), and chemical shifts (δ) are reported in parts per million (ppm) referenced to tetramethylsilane (^{1}H) or the internal (NMR) solvent signal (^{13}C). Mass spectra were acquired on a quadrupole orthogonal acceleration time-of-flight mass spectrometer. Samples were infused at 3 μL/min, and spectra were obtained in positive (negative) ionization mode with a resolution of 15 000 (fwhm) using leucine enkephalin as lock mass. Melting points (not corrected) were determined. The compounds were obtained in a pure form after column chromatography (70 230 mesh silica 60 was used as the stationary phase). CD measurements were performed on a spectropolarimeter. All spectroscopic measurements were performed in quartz cuvettes with an optical path length of 1 cm. Chemicals received from commercial sources were used without further purification. Solvents used in reactions were freshly distilled or were otherwise used as received. Photochemical reactions were performed in a photochemical reactor equipped with interchangeable light sources (300 and 350 nm lamps) using a quartz flask.

Computational Methods. The electronic circular dichroism (CD) spectra were calculated using TD-DFT with the B3LYP hybrid function combined with the 6-31G(d,p) basis set and PCM for chloroform. The excited states were calculated for up to the 15 lowest energies. The rotational strength velocity (R_{vel}) and length formalism (R_{len}) were calculated. Both formalisms were almost identical. Rotatory strengths were estimated in cgs units of 10^{-40} esu cm erg G^{-1}, where 1 esu cm erg G^{-1} corresponds to 3.336×10^{-15} C m J T^{-1} in SI units. The CD spectra of the individual conformers were visualized using SpecDis, version 1.61.[19a] The half-width at 1/e of the peak maximum σ value of 0.30 eV and R_{vel} were used in this work. The calculated CD spectra were not wavelength corrected.

Experimental and Characterization Data. *Synthesis of 2,7-Dimethoxycarbazole **1**.* Compound **1** was prepared according to a previously reported literature procedure.[15] mp, MS, ^{1}H NMR, and ^{13}C NMR were utilized to confirm the identity of the material.

*Synthesis of 9-(2-Ethylhexyl)-2,7-dimethoxycarbazole **2**.* To a solution of 2,7-dimethoxy-9*H*-carbazole **1** (0.34 g, 1.50 mmol) in acetone (12 mL) were added potassium carbonate (0.080 g, 0.60 mmol), potassium hydroxide (0.25 g, 4.50 mmol), and a catalytic amount of tetrabutylammonium hydrogensulfate; finally, 2-ethylhexyl bromide (0.32 g, 1.80 mmol) was added, and the reaction mixture was refluxed for 12 h. After 12 h, the reaction mixture was cooled to room temperature and diluted with ethyl acetate. The organic layer was washed with water and brine, dried over anhydrous Na_2SO_4, and filtered, and solvent was removed under reduced pressure. The residue was purified by silica-gel column chromatography using heptanes/acetone (20:1) as the eluent. Compound **2** (0.38 g, 75%) was obtained as yellow crystals. mp 86−88 °C. MS (EI) *m*/*z* 340 $[MH]^+$. HRMS (ESI-TOF) *m*/*z*: calcd for $C_{22}H_{29}NO_2$, 340.2198; found, 340.2271 [M + H]. ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C) δ 7.85 (d, *J* = 6.8 Hz, 2H), 6.82 (s, 3H), 6.81 (d, *J* = 1.6 Hz, 1H), 4.11−3.98 (m, 2H), 3.92 (s, 6H), 2.10−1.99 (m, 1H, CH), 1.42−1.26 (m, 8H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.88 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C) δ 158.2, 142.5, 120.2, 117.1, 106.7, 94.0, 55.8, 47.5, 39.3, 31.1, 29.0, 24.5, 23.2, 14.2, 11.1

*Synthesis of 9-(2-Ethylhexyl)-2,7-dimethoxycarbazole-3-carbaldehyde **3**.* To a solution of DMF (5.3 mL, 69 mmol) at 0 °C was added $POCl_3$ (3.4 mL, 37 mmol) dropwise, and the reaction mixture was stirred for 10 min to form the Vilsmeier salt. To this was added a solution of 9-(2-ethylhexyl)-2,7-dimethoxycarbazole **2** (1.55 g, 4.60 mmol) in DCE (10 mL), and the reaction mixture was stirred at room temperature for 2 h. The reaction mixture was then quenched with a 1 M KOAc solution. Ethyl acetate was added, and the two layers separated; the organic layer was washed with water and brine, dried over $MgSO_4$, and evaporated to dryness. Purification by column chromatography using acetone/heptane (1:5) as eluent gave aldehyde **3** (1.25 g, 74%) as a yellow solid. mp 134−136 °C. MS (ESI+) *m*/*z* 368 $[MH]^+$. HRMS (ESI-TOF) *m*/*z*: calcd for $C_{23}H_{29}NO_3$, 368.2147; found, 368.2220 [M + H]. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS) δ 10.47 (s, 1H), 8.44 (s, 1H), 7.89 (d, *J* = 8.4 Hz, 1H), 6.86 (dd, *J* = 8.5, 2.2 Hz, 1H), 6.80 (d, *J* = 2.1 Hz, 1H), 6.69 (s, 1H), 4.02 (d, *J* = 1.6 Hz, 1H), 4.00 (s, 1H), 3.91 (s, 3H), 2.05−1.97 (m, 1H), 1.41−1.27 (m, 8H), 0.94 (t, *J* = 7.4 Hz, 3H), 0.88 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C, TMS) δ 189.5, 161.0, 159.0, 146.6, 143.1,

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120.9, 120.6, 118.4, 117.3, 117.2, 107.9, 94.8, 90.9, 55.9, 55.8, 47.5, 39.2, 31.1, 28.9, 24.5, 23.1, 14.2, 11.1.

Synthesis of 3-(2-(2-Chloroquinolin-3-yl)vinyl)-9-(2-ethylhexyl)-2,7-dimethoxycarbazole **5**. A solution of aldehyde **3** (0.380 g, 1.03 mmol) was added dropwise to a stirred solution of phosphonium salt **4** (0.617 g, 1.12 mmol) and sodium hydride (0.062 g, 2.60 mmol) in dichloromethane at 0 °C, after which the reaction mixture was stirred for 3 h. The crude product was purified by silica gel column chromatography using acetone/heptane (1:10) as eluent to obtain compound **5** (0.535 g, 98%, $Z/E \sim 2{:}1$ from ^{1}H NMR) as a yellow solid. mp 166–168 °C. MS (ESI+) m/z 527 $[\mathrm{MH}]^+$. HRMS (ESI-TOF) m/z: calcd for $C_{33}H_{35}ClN_2O_2$, 527.2387; found, 527.2387 [M + H]. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS) δ 8.40 (d, J = 21.0 Hz), 8.25 (s, 1H), 8.04–7.92 (m), 7.85 (d, J = 8.0 Hz), 7.80–7.73 (m), 7.69 (t, J = 4.8 Hz), 7.66–7.53 (m), 7.52 (s), 7.49 (s), 7.41–7.30 (m), 7.13–7.11 (m), 7.09–7.05 (m), 6.88–6.83 (m), 6.80 (d, J = 4.1 Hz), 6.78–6.70 (m), 6.69 (d, J = 2.2 Hz), 6.66 (d, J = 2.2 Hz), 4.06 (dd, J = 7.4, 2.0 Hz), 4.02 (s, 3H), 4.00 (d, J = 2.1 Hz), 3.93 (s, 3H, OCH_3,minor isomer), 3.86 (s, 3H, OCH_3, major isomer), 3.83 (s, 3H, OCH_3, major isomer), 2.08–1.96 (m), 1.71–1.63 (m), 1.43–1.23 (m), 0.98–0.83 (m). ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C, TMS) δ 158.5, 158.3, 156.4, 156.0, 151.1, 150.6, 146.7, 146.6, 142.8, 142.7, 142.4, 142.3, 137.7, 137.1, 133.1, 131.7, 131.0, 130.0, 129.8, 129.4, 128.4, 128.2, 127.9, 127.7, 127.6, 127.3, 127.2, 127.0, 126.9, 123.9, 121.1, 120.5, 120.2, 118.5, 118.0, 117.1, 117.0, 117.0, 116.9, 116.4, 107.1, 106.8, 94.4, 94.2, 91.7, 91.6, 56.0, 55.9, 55.8, 55.7, 47.5, 47.4, 39.3, 35.6, 31.2, 31.1, 29.0, 28.9, 26.6, 26.5, 24.5, 23.2, 23.1, 22.8, 14.2, 11.1.

Synthesis of 10-Chloro,3,7-dimethoxy-5,11-diaza[6]helicene **6**. Argon was bubbled through a solution of compound **5** (0.150 g, 0.28 mmol, mixture of two isomers) in toluene (440 mL); later, iodine (0.094 g, 0.37 mmol) was added to it, and then excess propylene oxide was added to the solution. A Rayonet photochemical reactor (wavelength, 350 nm) was used for irradiation, and the reaction mixture was irradiated for 48–50 h, after which it was washed with aqueous $Na_2S_2O_3$, water, and brine, dried over anhydrous $MgSO_4$, and evaporated to afford a dark yellow residue. Purification by column chromatography using Et_2O/acetone/heptane (1:1:40) as eluent gave the racemic diaza[6]helicene **6** (0.079 g, 53%) as a light yellow solid. mp 242–244 °C. MS (ESI+) m/z = 525 $[\mathrm{MH}]^+$. HRMS (ESI-TOF) m/z: calcd for $C_{33}H_{33}ClN_2O_2$, 525.2231; found, 525.2277 [M + H]. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS) δ 8.61 (d, J = 8.9 Hz, 1H), 8.28–8.18 (m, 3H), 7.69–7.62 (m, 1H), 7.27–7.20 (m, 2H), 6.92 (d, J = 1.9 Hz, 1H), 6.50–6.41 (m, 2H), 4.25 (d, J = 7.5 Hz, 2H), 4.20 (s, 3H), 3.88 (s, 3H), 2.24–2.13 (m, 1H), 1.55–1.34 (m, 8H), 1.03 (t, J = 7.3 Hz, 3H), 0.90 (td, J = 7.0, 1.9 Hz, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, 25 °C, TMS) δ 157.3, 154.3, 151.2, 143.4, 141.7, 141.1, 131.7, 128.6, 128.2, 126.1, 125.5, 125.2, 124.4, 124.0, 123.4, 123.3, 119.6, 117.5, 117.4, 112.3, 106.3, 93.6, 92.9, 56.3, 55.7, 47.7, 39.7, 31.3, 29.2, 24.8, 23.2, 14.2, 11.1.

Synthesis of 3,7-Dimethoxy-10-[(S)-α-(methyl benzylamino)]-5,11-diaza[6]helicene **7**. (*S*)-*α*-Methyl benzylamine (37 μL, 0.29 mmol), Cs_2CO_3 (0.931 g, 2.86 mmol), *rac*-BINAP (0.007 g, 5 mol %), and $Pd(OAc)_2$ (0.005 g, 10 mol %) were added to a solution of **6** (0.120 g, 0.23 mmol) in dry toluene (25 mL), and the reaction mixture was stirred at 80 °C for 12 h. Subsequently, the mixture was diluted with ethyl acetate (40 mL) and washed with water (3 × 20 mL). The organic fraction was dried over $MgSO_4$ and filtered, and the solvent was removed under vacuum. After column chromatographic purification using Et_2O/acetone/heptane (1:1:20) as eluent, a 1:1 mixture of diastereomers (0.074 g, 53%) was obtained as a yellow solid. These diastereomers were readily separated by silica gel column chromatography. mp 77–78 °C. MS (ESI+) m/z = 610 $[\mathrm{MH}]^+$. HRMS (ESI-TOF) m/z: calcd for $C_{41}H_{43}N_3O_2$, 610.3355; found, 610.3431 [M + H]. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS, single diastereomer) δ 8.45 (d, J = 8.7 Hz, 1H), 8.00 (d, J = 7.1 Hz, 1H), 7.88 (d, J = 7.6 Hz, 1H), 7.73 (d, J = 8.8 Hz, 1H), 7.60 (d, J = 7.2 Hz, 2H), 7.45 (t, J = 6.9 Hz, 1H), 7.38 (t, J = 7.4 Hz, 2H), 7.31–7.26 (m, 1H), 7.13 (s, 1H), 6.92–6.85 (m, 2H), 6.69 (d, J = 8.9 Hz, 1H), 6.43 (dd, J = 8.9, 2.3 Hz, 1H), 5.85–5.76 (m, 1H), 5.59 (d, J = 6.6 Hz, 1H), 4.22 (d, J = 7.3 Hz, 2H), 4.16 (s, 3H), 3.86 (s, 3H), 2.21–2.11 (m, 1H), 1.82 (d, J = 6.7 Hz, 3H), 1.51–1.28 (m, 8H), 1.00 (t, J = 7.3 Hz, 3H), 0.89 (t, J = 6.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C, TMS) δ 157.0, 154.2, 152.7, 141.4, 141.0, 131.1, 128.6, 128.1, 127.9, 127.1, 126.8, 126.3, 126.1, 124.3, 122.8, 122.7, 121.9, 121.6, 119.6, 117.8, 115.0, 112.2, 106.2, 93.4, 91.9, 56.2, 55.7, 47.6, 39.7, 31.3, 31.3, 29.9, 29.2, 29.1, 24.8, 23.2, 22.7, 14.2, 11.3, 11.1.

Synthesis of 2-Bromo-3,7-dimethoxy-10-[(S)-α-(methyl benzylamino)]-5,11-diaza[6]helicene **8**. To a solution of compound **7** (25 mg, 0.041 mmol) in chloroform (5 mL) at −40 °C was added NBS (6.9 mg, 0.038 mmol), and the reaction mixture was stirred at this temperature for 3 h. After 3 h, the reaction mixture was diluted with ethyl acetate. The organic layer was washed with water and brine and dried over $MgSO_4$, and the solvent was removed under vacuum. The crude product was purified by silica-gel column chromatography using heptane/CH_2Cl_2/acetone (20:1:1) as the eluent. Compound **8** (23 mg, 82%) was obtained as yellow solid. mp 70–73 °C, MS (ESI+) m/z 689 $[\mathrm{MH}]^+$, HRMS (ESI-TOF) m/z: calcd for $C_{41}H_{42}BrN_3O_2$, 688.2534; found, 688.2536, 690.2526, 691.2549 [M + H]. ^{1}H NMR (600 MHz, $CDCl_3$, 25 °C, TMS) δ 8.46 (d, J = 8.7 Hz, 1H), 7.94 (d, J = 8.1 Hz, 1H), 7.86 (d, J = 8.2 Hz, 1H), 7.76 (d, J = 8.7 Hz, 1H), 7.62 (d, J = 7.7 Hz, 2H), 7.54 (t, J = 7.5 Hz, 1H), 7.40 (t, J = 7.7 Hz, 2H), 7.32–7.27 (m, 1H), 7.13 (s, 1H), 6.92 (t, J = 7.3 Hz, 1H), 6.89 (s, 1H), 6.82 (s, 1H), 5.84–5.78 (m, 1H), 5.66–5.59 (m, 1H), 4.25 (d, J = 7.3 Hz, 2H), 4.18 (s, 3H), 3.97 (s, 3H), 2.18–2.11 (m, 1H), 1.83 (d, J = 6.7 Hz, 3H), 1.51–1.39 (m, 8H), 1.04–0.99 (m, 3H), 0.91–0.87 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C, TMS) δ 154.7, 152.8, 152.6, 145.1, 144.8, 141.2, 139.7, 131.0, 129.7, 128.9, 128.4, 127.9, 127.4, 127.0, 126.5, 124.3, 123.0, 122.6, 121.5, 121.4, 121.1, 119.8, 118.3, 115.4, 111.1, 102.5, 92.1, 91.7, 56.5, 56.2, 50.9, 47.6, 39.8, 31.4, 29.2, 24.8, 23.1, 22.4, 14.2, 11.3.

Synthesis of 2-Formyl-3,7-dimethoxy-10-[(S)-α-(methyl benzylamino)]-5,11-diaza[6]helicene **9**. To a solution of DMF (0.050 mL, 0.66 mmol) at 0 °C was added $POCl_3$ (0.03 mL, 0.33 mmol) dropwise, and the reaction mixture was stirred for 10 min to form the Vilsmeier salt. To this was added a solution of compound **7** (20 mg, 0.033 mmol) in DCE (3 mL), and the reaction mixture was stirred at room temperature for 3 h. The reaction mixture was poured into crushed ice. Ethyl acetate was added, the two layers were separated, and the organic layer was washed with water and brine, and dried over $MgSO_4$, and evaporated to dryness. Purification by column chromatography using acetone/heptane (1:5) as eluent gave aldehyde **9** (8.9 mg, 42%) as a yellow solid. mp 92–94 °C. MS (ESI+) m/z 638 $[\mathrm{MH}]^+$. HRMS (ESI-TOF) m/z: calcd for $C_{42}H_{43}N_3O_3 + NH_4$, 655.3304; found, 655.3367 $[M + NH_4]$. ^{1}H NMR (300 MHz, $CDCl_3$, 25 °C, TMS) δ 9.91 (s, 1H), 8.46 (d, J = 8.8 Hz, 1H), 7.95 (d, J = 8.1 Hz, 1H), 7.88 (d, J = 7.2 Hz, 1H), 7.77 (d, J = 8.9 Hz, 1H), 7.62 (d, J = 7.4 Hz, 2H), 7.53–7.45 (m, 1H), 7.41 (t, J = 7.4 Hz, 2H), 7.33–7.27 (m, 1H), 7.16 (s, 1H), 7.13 (s, 1H), 6.86–6.78 (m, 2H), 5.89–5.77 (m, 1H), 5.60 (d, J = 5.0 Hz, 1H), 4.26 (d, J = 7.3 Hz, 2H), 4.18 (s, 3H), 4.00 (s, 3H), 2.21–2.12 (m, 1H), 1.82 (d, J = 6.7 Hz, 3H), 1.56–1.32 (m, 8H), 1.04 (td, J = 7.3, 2.1 Hz, 3H), 0.90 (t, J = 6.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C, TMS) δ 189.6, 158.8, 155.1, 152.6, 145.1, 144.5, 142.0, 130.1, 128.9, 128.6, 127.9, 127.4, 127.0, 124.4, 123.3, 122.54, 122.49, 121.5, 121.45, 121.41, 121.3, 120.0, 119.9, 117.9, 117.5, 116.0, 112.4, 91.8, 90.8, 56.2, 55.9, 50.8, 47.7, 39.8, 32.1, 31.4, 29.2, 24.8, 23.1, 14.2, 11.3.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Theoretical CD spectra for *conf1* of the diastereomer (*M*,*S*)-(−)-**7** with methyl and (*S*)- ethylhexyl moieties. Conformation analysis of (*P*,*S*)-(+)-**7** and (*M*,*S*)-(−)-**7**. ^{1}H and ^{13}C NMR spectra of the novel precursors and diaza[6]helicenes and substituted derivatives. Cartesian coordinates of (*P*,*S*)-(+)-**7** and (*M*,*S*)-(−)-**7** conformers. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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