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Synthesis, Conformation and Chiroptical Properties of Diaryl Esters of Tartaric Acid†

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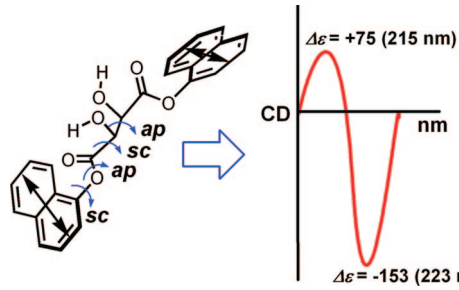

Previously unknown diaryl esters of L-tartaric acid have been synthesized. Their conformations have been studied by DFT calculations, NMR and circular dichroism spectroscopy in solution, as well as by X-ray diffraction in the crystalline state. The four-carbon tartrate chain of diaryl esters was found to be extended in all cases, with a higher degree of nonplanarity in the crystals. Dinaphthyl tartrates show unusually strong exciton Cotton effects ($A = -228$ for di-1-naphthyl L-tartrate) due to the coupling of allowed $1B_b$ transitions in naphthyl chromophores, despite the acyclic structure and significant distance (over 10 Å) between the two chromophores.

Introduction

Tartaric acid belongs to a narrow group of very important optically active compounds. The study of its stereoisomeric molecules led Pasteur over 160 years ago to the discovery of enantiomerism.[1] A hundred years later, Bijvoet for the first time experimentally determined the absolute configuration of an organic molecule, analyzing the anomalous scattering of zirconium Kα X-rays by crystals of sodium rubidium tartrate.[2] The importance of tartaric acid in the development of organic stereochemistry has been strengthened by the role of its derivatives in life sciences and chemistry, especially by the wide applications of its derivatives in the synthesis of numerous chiral organic compounds. In synthetic applications, tartaric acid has served not only as the source of chiral building blocks but also as the precursor of chiral ligands, auxiliaries, and resolving agents.[3] Among derivatives of tartaric acid, its dialkyl esters are most frequently used, not only for the preparation of other tartaric acid derivatives but also in asymmetric catalysis, for example, as chiral ligands in the Sharpless−Katsuki asymmetric epoxidation,[4] kinetic resolution of racemic allyl alcohols,[5] asymmetric synthesis of sulfoxides by the Kagan−Modena method,[6] asymmetric Simmons−Smith reaction,[7,8] asymmetric allylation,[9,10] asymmetric allylbora-

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† Dedicated to Professor D. A. Lightner on the occasion of his 70th birthday.

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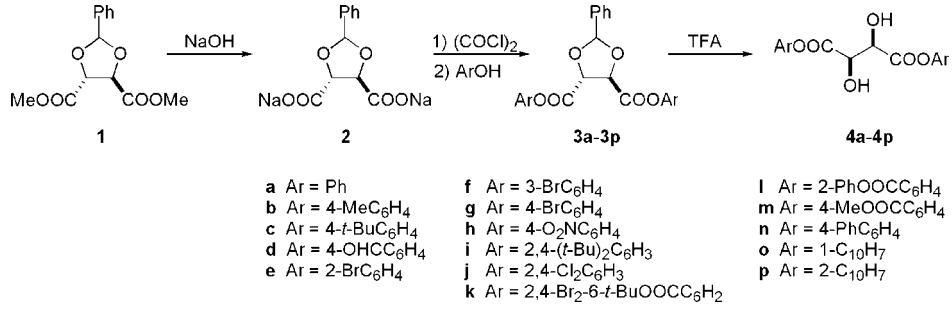
SCHEME 1. Synthesis of Diaryl Esters 4a−p of L-Tartaric Acid



tion developed by Roush,[11] and homoallenylboration of aldehydes developed by Brown.[12]

In contrast to the wide availability (including commercial) of dialkyl tartrates, diaryl tartrates have remained until now virtually unknown. This is quite obvious considering the difficulties encountered in chemoselective esterification of hydroxy acids with phenols. Whereas dialkyl tartrates are readily available by Fischer esterification of tartaric acid or transesterification of a tartrate with the use of excess alcohol, such a procedure is not applicable to phenols. In fact, we tried many general procedures for acid activation toward the synthesis of aryl esters, as described in the literature; however, they did not afford any aryl ester on reaction with tartaric acid, the difficulty apparently arising from the competitive reaction of hydroxy group present in the acid. While seeking a procedure for preparation of diaryl tartrates directly from tartaric acid, we came across a method for direct formation of dinaphthyl esters of malic acid with the use of *N,N*-bis(2-oxo-3-oxazolidinyl)phosphorodiamidic chloride for the activation of carboxylic group.[13] In our hands, when applied to tartaric acid, this method failed to give any ester on reaction with 2-naphthol.

Results and Discussion

Synthesis of Diaryl L-Tartrates. It was obvious that the synthesis of diaryl L-tartrates would require protection of the tartrate hydroxy groups. Since the esters of phenols are prone to hydrolysis under basic conditions (to generate resonance-stabilized phenolate ion), the protecting group would require removal conditions orthogonal to those for the ester group. Benzylidene protecting group for the diols is known to be selectively removed under mildly acidic (trifluoroacetic acid in dichloromethane) or neutral (hydrogenolysis with Pd catalysis) conditions. We therefore adopted this indirect method for the synthesis of diaryl L-tartrates (Scheme 1).

Starting from the known dimethyl 2,3-*O*-benzylidene-L-tartrate (**1**),[14] which can be obtained easily and in high yield from dimethyl L-tartrate,[15] we were able to obtain the disodium salt **2** by ester saponification with ethanolic NaOH (yield 98%). Dry disodium salt **2** was converted to unstable dichloride by the reaction with oxalyl chloride in dry toluene containing a catalytic amount of DMF. The dichloride was immediately subjected to the reaction with phenol or a naphthol in the presence of pyridine to yield diesters **3a**−**p** (30−67%). Low yields of diesters **3d**,**h**,**m**,**l** can be ascribed to their lower stability toward workup conditions, due to the presence of electron-withdrawing substituents in the phenol ring. The hydrolysis of the dioxolane protecting group in **3** could be selectively achieved with the aid of TFA−H_2O in dichloromethane solution (yield 51−92%). Diaryl L-tartrates **4a**−**p** were characterized by spectroscopic methods. In particular, the ^{1}H NMR spectra showed the absence of the dioxolane C*H*Ph proton signal which is present in **3a**−**p** (δ 6.2−6.5). Signals of the protons attached to the chiral carbon atoms in diaryl L-tartrates **4a**−**p** were found in the range δ 5.0−5.5, apparently shifted downfield by ca. 1 ppm in comparison to the corresponding signals of dialkyl tartrates. It is of interest to note that deacetalization of diaryl ester **5**, a derivative of 3,5-dibromosalicylic acid obtained by a route similar to that reported here, is described to yield a product characterized by a signal of the protons at the chiral carbon atoms shifted to δ 5.92−5.95.[16] This may suggest that the structure of the product is more likely a dilactone **6** or an *O*,*O*′-diacylated diacid **7** (Scheme 2).

Conformational Preferences of Diaryl L-Tartrates. The conformational preferences of L-tartaric acid and its alkyl ester, amide, and nitrile derivatives have been a subject of extensive studies in the past.[17−21] Central to the conformational characteristic of these acyclic, highly functionalized molecules is the extended (*trans*) or bent (*gauche*) conformation of the four-carbon chain. This can be visualized in Newman projections of the three possible conformers, T, G^-, G^+ (Scheme 3).

According to accumulated evidence, tartaric acid, its salts, alkyl esters, and NH-amides exist in an extended (T) conformation. Bent (G^-) conformers are dominant in *N*,*N*,*N*′,*N*′-tetraalkyltartramides,[17] whereas G^+ conformers are the most populated

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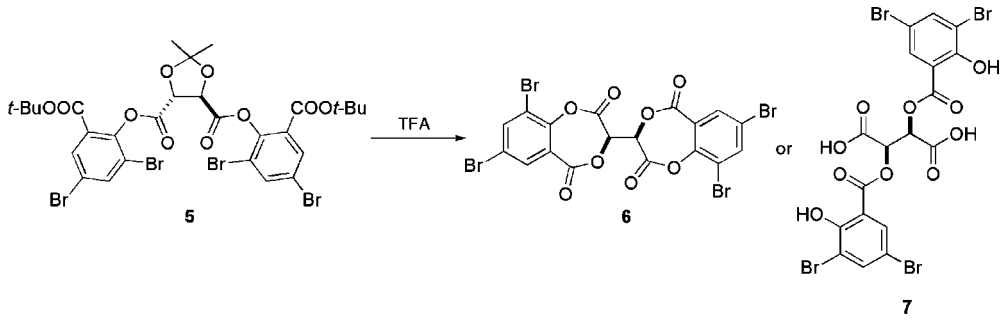
SCHEME 2. Possible Products of Hydrolysis of Acetal 5



SCHEME 3. Conformational Preferences of L-Tartaric Acid Derivatives and Definition of Torsion Angles

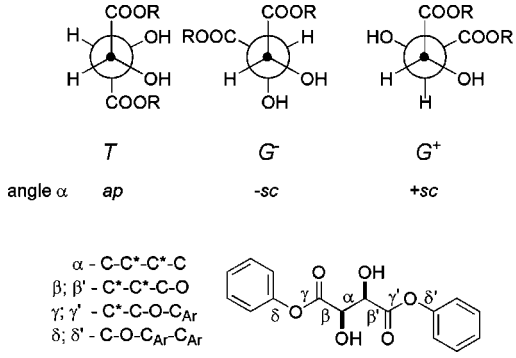


TABLE 1. Diagnostic Coupling Constants from the NMR Spectra of Diaryl L-Tartrates in Acetone-d_6 Solution

compd	$^3J_{H,H}$ (Hz)	$^2J_{C,H}$ (Hz)
4a	2.5	<1
4o	2.3	<1
4p	2.6	<1

species in the case of tartarodinitriles.[19] In all cases, the conformational equilibrium results from contributions of steric and stereoelectronic effects, the latter mainly due to antiparallel 1,3-dipole/dipole interactions of the CH and CO bonds.[18]

NMR Study. $^3J_{H,H}$ and $^2J_{C,H}$ coupling constants of the protons at chiral carbon atoms of the tartrate molecule are listed in Table 1.

These coupling constants characterize the conformation of the four-atom carbon chain in solution.[17] Low values of the coupling constants are characteristic of preferential extended (*T*) conformation of the tartrate carbon chain. This conformation is therefore postulated for diaryl L-tartrates such as **4a**, **4o**, and **4p**, regardless the substitution pattern of the aryl group.

X-ray Diffraction Study. The investigated diphenyl (**4a**) and di-2-naphthyl (**4p**) L-tartrate molecules constitute the first example of tartaric acid diaryl esters for which the crystal structure has been determined.[22] Figure 1 illustrates the conformation in the crystal and numbering scheme of the investigated molecules. Di-2-naphthyl tartrate crystallizes with two symmetry-independent molecules (labeled with and without primes) which differ in their molecular conformation.

Potentially C_2 symmetrical, the molecules do not attain C_2 symmetry in their crystals, and departures from this symmetry are substantial (Table 2). As in the vast majority of optically active tartaric acid dialkyl esters so far investigated by X-ray diffraction,[17b,23−26] the conformation around the C*−C* bond linking two chiral centers is staggered and such that two carboxylate groups are *trans* (*T*), two adjacent C−OH bonds are *gauche* (G^-) and two adjacent C−H bonds are *gauche* (G^+) (Table 2). However, deviations from the ideal staggered conformation are significant, the largest being in diphenyl L-tartrate (angle α = 147.1(4)°). In this compound, the hydroxy groups are positioned mutually perpendicular (torsion angle −93.4(4)°), instead of the expected G^- orientation. Conse-

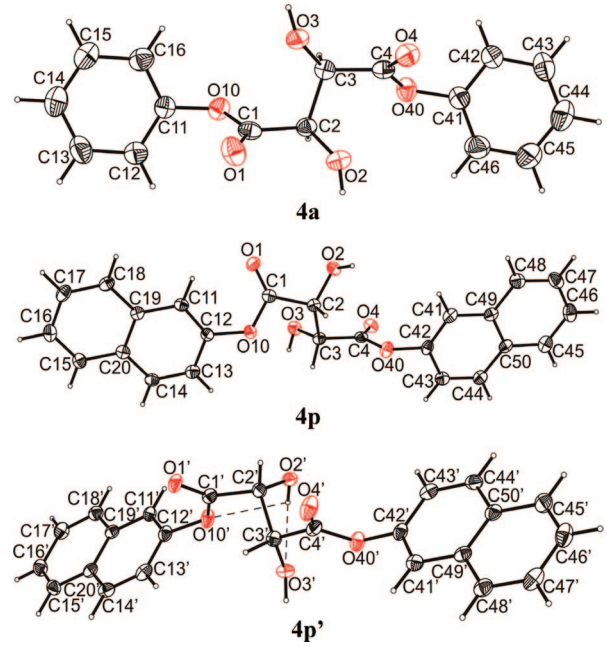


FIGURE 1. Illustration of conformers of the investigated molecules with atom numbering scheme for (**4a**) *T*(*sp,sp*), (**4p**), *T*(*sp,sp*), and (**4p′**) *T*(*ap,ap*). Thermal ellipsoids are drawn at 40% probability level. Dashed lines illustrate intramolecular hydrogen bonds; *sp* and *ap* refer to relative orientation of the vicinal C═O and C−O(H) bonds.

TABLE 2. Selected Torsion Angles (deg) Describing the Molecular Conformation

torsion angle	4a	4p	4p′
C1−C2−C3−C4 (α)	147.1(4)	162.1(2)	−154.5(2)
C3−C2−C1−O10 (β)	71.5(4)	64.1(2)	−84.2(2)
C2−C3−C4−O40 (β′)	69.2(5)	66.6(2)	−102.1(2)
C2−C1−O10−C11 (C12) (γ)	−178.1(3)	−172.0(2)	167.7(2)
C3−C4−O40−C41 (C42) (γ′)	−173.9(4)	−177.2(2)	178.0(2)
C1−O10−C11(C12)−C12(C11) (δ)	−66.1(6)	−51.5(3)	115.3(2)
C1−O10−C11(C12)−C16(C13) (δ)	117.4(5)	133.2(2)	−70.5(3)
C4−O40−C41(C42)−C42(C41) (δ′)	−76.4(6)	101.7(2)	77.2(3)
C4−O40−C41(C42)−C46(C43) (δ′)	107.5(5)	−80.5(3)	−106.6(2)
O2−C2−C3−O3	−93.4(4)	−75.6(2)	−44.0(2)
H2−C2−C3−H3	25.1	43.2	80.5
O1═C1−C2−O2	11.3(6)	5.1(3)	−144.0(2)
O4═C4−C3−O3	13.3(7)	5.2(3)	−164.2(2)

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quently, the torsion angle between the C*−H bonds situated at the chiral centers is only 25°. In the two independent molecules of di-2-naphthyl L-tartrate, these deviations are realized in a supplementary fashion, i.e., the values of the O2−C2*−C3*−O3 torsion angles are in one molecule bigger and in the other smaller by 16° than the ideal value of −60° (Table 2).

The usually observed coplanarity of ester and proximal hydroxy functionalities is retained in two of the three molecules (i.e., **4a** and **4p**), although to a different extent. In these two molecules, the α-hydroxy oxygen eclipses the carbonyl oxygen (*sp* conformation), while the molecule **4p′** shows significant nonplanarity of both α-hydroxyester moieties, the α-hydroxy oxygen lying closer to the naphtol oxygen (an approximate *ap* conformation). Pronounced nonplanarity of the O1′═C1′−C2′−O2′ fragment allows formation of two intramolecular hydrogen bonds with the same O2′-H donor but two different acceptors (O3′ and O10′) (Table A, Supporting Information), a situation not possible within a planar α-hydroxy carboxylate fragment, where either none or only one intramolecular hydrogen bond can be formed. The O2′ hydroxyl is additionally involved in one intermolecular hydrogen bond, thus taking part in the formation of a rarely observed four-center hydrogen bond. Clearly, this is a result of an apparent lack of the hydrogen-bond donors: in all three molecules, the ratio of potential hydrogen bond donors to hydrogen bond acceptors is 2:6. In the crystal structure of diphenyl ester, this shortage of hydrogen-bond donors is compensated by engaging each of the two hydroxy groups as donors in two intermolecular hydrogen bonds. One can envisage that realization of such a hydrogen-bond pattern is sterically demanding, and this is probably the reason why the diphenyl ester molecule adopts in the solid state a nearly *ac* conformation of its four-carbon chain and, moreover, the hydrogen bonds formed in this crystal are far from being linear (Table A, Supporting Information).

Only in structure **4p′** is one stabilizing 1,3-C═O/C−H dipole−dipole interaction realized. Worthy of note is the mutual orientation of the aryl substituents, which are aligned nearly parallel in all three molecules. In the diphenyl ester molecule, the two phenyl rings are inclined at an angle of 11.3(4)°, while in both crystallographically independent molecules of dinaphthyl ester the average interplanar angle is only 3.2(2)°.

In both investigated crystal structures, molecules connected by hydrogen bonds form layers parallel to the (001) lattice plane. Phenyl or naphthyl groups are concentrated on both sides of these layers, and one unit cell contains two such layers, as illustrated in Figure 2.

Compared to optically active tartaric acid and NH-tartramides, tartrates display much higher conformational flexibility manifested in the ease with which they adjust to packing requirements in their crystals. Diaryl tartrates seem to outweigh dialkyltartrates in this respect by not only being able to switch the conformation around the C(sp^3)−C(sp^2) bonds (angle β) from *sp* to *ap* but also in displaying a significant deviation from the extended (*T*) four-carbon chain conformation, a phenomenon so far unprecedented in tartrates.

DFT Calculations. In order to obtain a more quantitative insight into the conformer population of isolated molecules of diaryl tartrates, we selected diphenyl (**4a**), di-1-naphthyl (**4o**), and di-2-naphthyl (**4p**) L-tartrates, representing various patterns of aryl ring substitution in relation to the ester C−O bond, for computational modeling, with the use of Gaussian03[27] software (for computational details, see the Supporting Information).

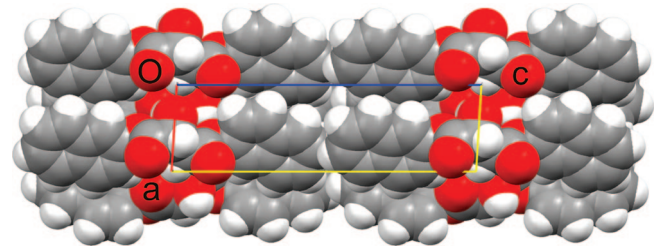

FIGURE 2. van der Waals representation of bimolecular hydrophobic layers characteristic for both investigated diaryl L-tartrates and exemplified by diphenyl L-tartrate (**4a**).

At the B3LYP/6-311++G(2D,2P) level of calculation, we found, within the 2.0 kcal·mol^{-1} free energy window, two stable conformers for **4a**, four in the case of **4o** and three for **4p**. Their relative free energies, populations, symmetries, and consecutive torsion angles along the molecule chain are listed in Table 3. Figure 3 shows the structures of these conformers, including the available intramolecular hydrogen bonds.

In general, all calculated structures belong to the extended (*T*) family, with torsion angle α in the range 171−174°. This is in contrast to the data from the X-ray study (see Table 2) where angle α is found to be significantly smaller (147−162°). All calculated structures shown in Figure 3 are stabilized by at least one intramolecular hydrogen bond of the length 2.05−2.11 Å, involving OH donor and vicinal ester carbonyl group. For this reason, angle β is *sc* in all cases, except in structures not stabilized by such a hydrogen bond. In these structures (**4a**, conformer 2; **4o**, conformers 3 and 4), one hydroxy group is engaged in weak hydrogen bonding with two vicinal oxygens atoms, i.e., the ester and the other hydroxy group (Figure 3), to yield angle β ca. −110°. Only these conformers are stabilized by one 1,3-C═O/C−H dipole interaction. Furthermore, an extended conformation is found for the tartrate structure involving the C*−C−O−C_{Ar} bonds (angle γ). In all cases, the calculated angles γ are close to ideal *ap* (180°). Incidentally, in the crystal structures of **4a** and **4p** angle γ shows a higher degree of deviation from the ideal value for the *ap* conformation (see Table 2). Finally, angle δ describing nonplanarity of the aryl ring and the ester C−O bond is found in the range 68°−91°, described as *sc*. This degree of nonplanarity is expected for the derivatives of phenols, such as ethers and esters. The corresponding values of angle δ obtained from the crystal structures of **4a** and **4p** are negative.

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TABLE 3. Calculated at the B3LYP/6-311++G(2D,2P) Level Relative Free Energies (ΔG), Populations, Symmetries, And Torsion Angles α, β, γ, δ for Low Energy Conformers of 4a, 4o, and 4p.

					torsion angles[a] (deg)			
ester	conformer	ΔG (kcal·mol^{-1})	population (%)	symmetry	α	β; β'	γ; γ'	δ; δ'[b]
4a	conf 1	**0.00**	**85**	C_2	171.7	61.9	−176.3	73.4
	conf 2	1.02	15	C_1	−173.1	59.1; −112.2	177.4; −178.8	74.4; −78.2
4o	conf 1	**0.00**	**50**	C_1	171.3	58.0;61.9	178.9; −176.8	74.5; −91.1
	conf 2	0.21	35	C_2	171.4	58.2	178.7	91.4
	conf 3	0.88	11	C_1	−174.2	55.1; −111.8	178.6; 177.4	89.7; −78.7
	conf 4	1.35	4	C_1	−174.4	55.8; −107.9	179.0; 179.6	91.3; −91.3
4p	conf 1	**0.00**	**58**	C_1	171.4	62.2;61.3	−174.7; −176.3	68.9; 83.7
	conf 2	0.40	29	C_2	170.8	61.3	−175.9	78.2
	conf 3	0.85	13	C_2	171.3	62.3	−174.3	67.9

[a] For definition of torsion angles, see Scheme 2. [b] The smaller of the two torsion angles is shown.

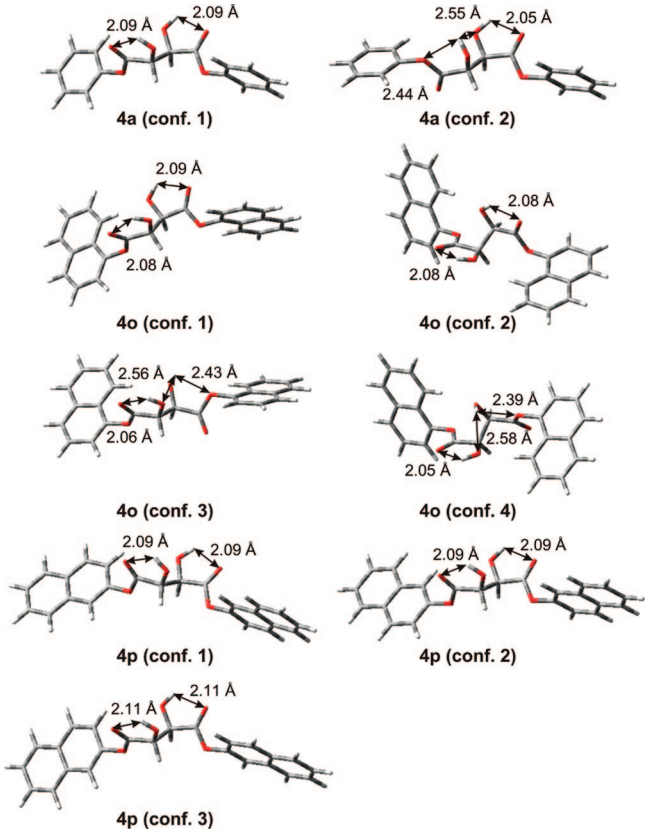

FIGURE 3. Calculated at B3LYP/6-311++G(2D,2P) level structures of low energy conformers of **4a**, **4o**, and **4p** with intramolecular hydrogen bonds shown.

In general, calculated typical structures of diaryl L-tartrates stabilized by intramolecular OH···O=C hydrogen bond(s) can be shortly characterized by a sequence of torsion angles: α (*ap*), β (*sc*), γ (*ap*), δ (*sc*). On the other hand, higher energy structures of C_1 symmetry with one bifurcated hydrogen bond can be described as α (*ap*), β (*ac*), γ (*ap*), δ (*sc*). One should bear in mind, however, that free energy differences between conformers of diaryl esters are in general not high and in solution interactions with the solvent molecules may bring about significant shifts in conformer populations.

Circular Dichroism and Optical Rotation of Diaryl L-Tartrates. Diaryl esters of L-tartaric acid represent rare examples of molecules bearing an aromatic chromophore attached to a chiral carboxylic acid through an ester bond. Although these molecules are acyclic and, according to DFT calculations on isolated molecules, possess well-defined conformations, it is not clear if similar conformational restrictions apply to the tartrates in solution. Significant Cotton effects, if observed within electronic transitions of the aryl chromophores, would attest to limited conformational freedom of diaryl L-tartrates in solution. The CD/UV spectra of diaryl L-tartrates in acetonitrile solution are shown in Figures 4−6.

The esters of phenol and its derivatives **4a**−**n** (Figure 4) are characterized by a weak long-wavelength absorption due to ^1L_b-type transition (not observed in the CD spectra) and a stronger ^1L_a band, located at ca. 220 nm in diphenyl L-tartrate (**4a**). This band is shifted to a longer wavelength and becomes more intensive in substituted phenyl L-tartrates **4b**−**m**. It is associated with a negative Cotton effect of moderate intensity ($\Delta\varepsilon$ −4 to −12) in the CD spectra. The origin of this Cotton effect is not fully understood at present. In addition to ^1L_a transition which is observed in the UV spectrum there is a possibility of contribution from the carboxylate n−π* transition. This transition is of weak oscillator strength but in the case of dialkyl L-tartrates it can be observed as a distinct negative Cotton effect at ca. 220 nm.[17,18] Nevertheless, the long-wavelength (220−240 nm) negative Cotton effect appears to be characteristic of absolute configuration and conformation of both dialkyl and diaryl L-tartrates, and its presence has been confirmed by our TDDFT calculation of the CD spectrum for the most stable conformer of **4a**. Note that the 4-nitrophenyl derivative **4h** displays an additional negative Cotton effect in the CD spectrum at ca. 280 nm, apparently due to a transition involving the π-electron system of the nitro group.

The UV spectrum of diester **4n** is remarkable due to the presence of a strong biphenyl band at 252 nm (ε 37700). In the CD spectrum, a bisignate Cotton effect is seen within the 252 nm band ($\Delta\varepsilon$ −9.5 at 262 nm, + 3 at 239 nm). This suggests that the bisignate Cotton effect is of exciton type due to the interaction of the electronic transition moments of the conjugation band in the two biphenyl chromophores. A similar exciton Cotton effect can be seen in the CD spectrum of 4-methoxycarbonyl diester **4m**. In this case, the bisignate Cotton effect ($\Delta\varepsilon$ −9 at 240 nm, +3 at 221 nm) is due to exciton interaction of the two substituted benzoate chromophores.

An even more pronounced exciton coupling mechanism is observed in the CD spectra of dinaphthyl L-tartrates **4o** and **4p**. The intense ^1B_b transition in naphthalene chromophores of **4o** and **4p** is located at ca. 220 nm (ε ∼70000) and generates very strong negative exciton-coupled Cotton effects, i.e., $\Delta\varepsilon$ −153 at 223 nm, + 75 at 215 nm for **4o** and $\Delta\varepsilon$ −35 at 226 nm, + 23 at 215 nm for **4p** (Figures 5 and 6).

Large magnitudes of the Cotton effects may appear surprising given the number of low energy conformers contributing to the

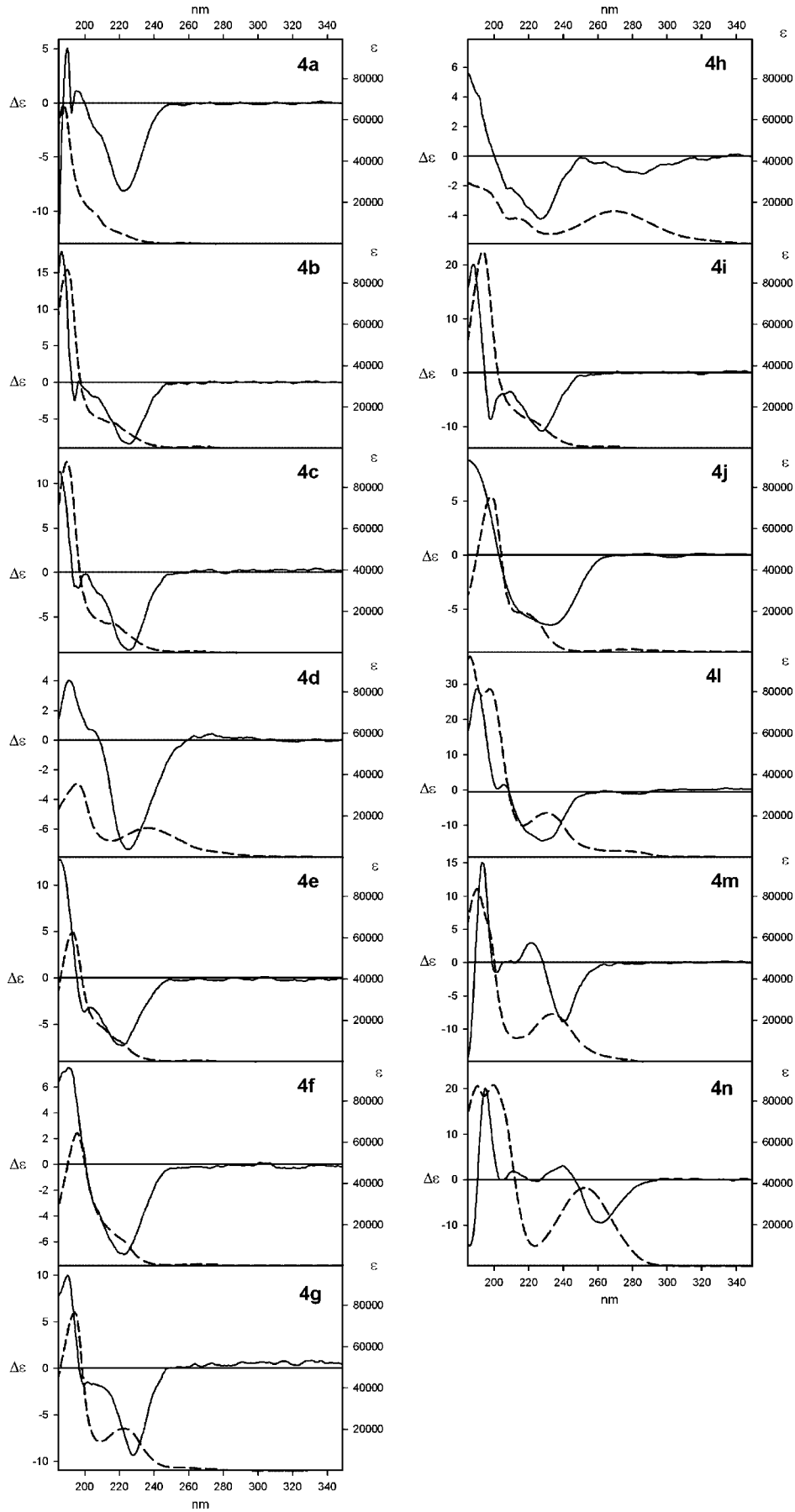

FIGURE 4. CD (solid lines) and UV (dashed lines) spectra of esters **4a**−**n** measured in acetonitrile solutions.

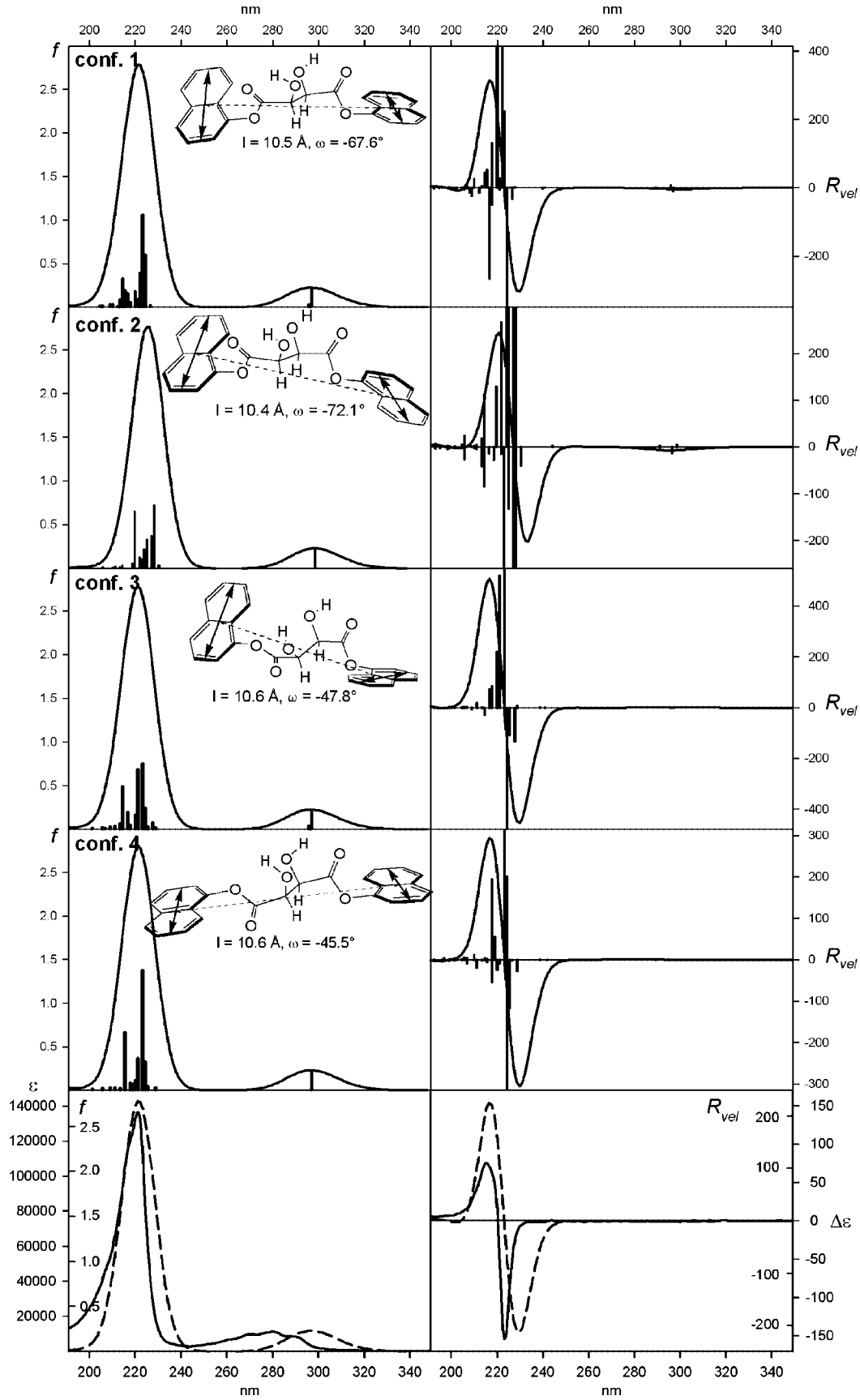

FIGURE 5. Calculated at TDDFT/B2LYP/6-311++G(2D,2P) level UV (left panels) and CD (right panels) spectra for individual conformers of **4o**, Boltzmann-averaged calculated UV and CD spectra (dashed lines) and experimental UV and CD spectra (solid lines, bottom panels) of **4o**. Vertical bars represent oscillator (*f*) or rotatory strengths (*R*), respectively. The rotatory strengths *R* were calculated in velocity representations. All calculated spectra were wavelength corrected to match the experimental short wavelength λ_{max} value in the UV spectrum.

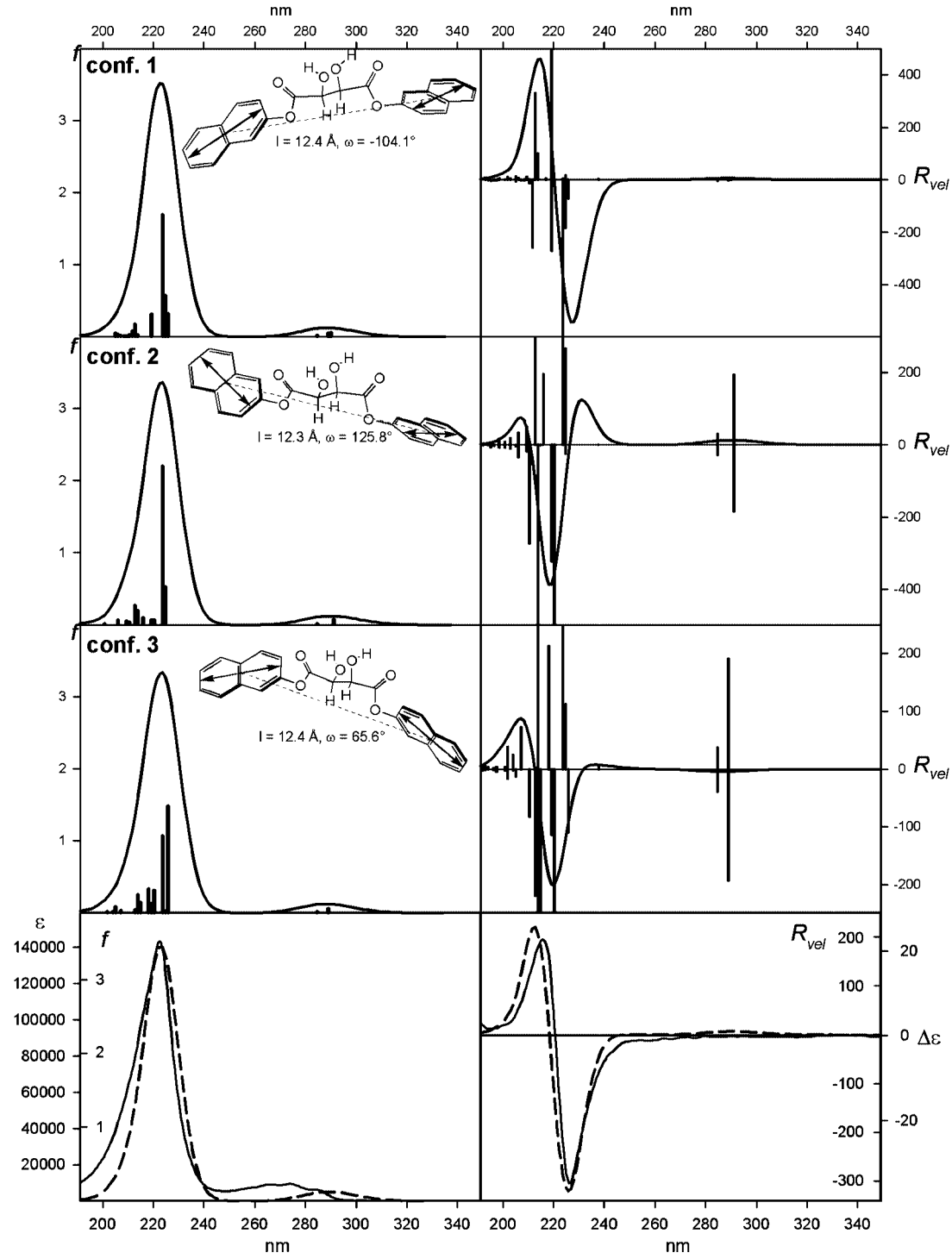

FIGURE 6. Calculated at TDDFT/B2LYP/6-311++G(2D,2P) level UV (left panels) and CD (right panels) spectra for individual conformers of **4p**, Boltzmann-averaged calculated UV and CD spectra (dashed lines), and experimental UV and CD spectra (solid lines, bottom panels) of **4p**. Vertical bars represent oscillator (*f*) or rotatory strengths (*R*), respectively. The rotatory strengths *R* were calculated in velocity representations. All calculated spectra were wavelength corrected to match the experimental short wavelength λ_{max} value in the UV spectrum.

population (four in the case of **4o**, three in the case of **4p**, Table 3). TDDFT calculations of the CD spectra of individual conformers of **4o** and **4p** (Figures 4 and 5) provide rationalization of the observed high intensity Cotton effects ($A = -228$ for **4o**, -58 for **4p**). All four conformers of **4o** are characterized by a negative helicity of the ^1B_b transition electric dipole moments (the dihedral angle between the electric dipole transition moments is $-45°$ to $-72°$); hence, all four conformers generate negative exciton Cotton effects. This results in a very strong experimental negative Cotton effect, despite a rather large spatial separation of the two naphthalene chromophores (ca. 10.5 Å). Conversely, smaller amplitude of the exciton Cotton effect of **4p** is the result of opposite sign contributions of conformers 1 (negative) and 2 (positive), while triple-sign exciton Cotton effect (−/+/−) was calculated for conformer 3 of **4p**. The population-averaged CD spectrum of **4p** is still of negative amplitude ($A = -58$) due to a dominant contribution (58% population) of conformer 1. We note that the sign and magnitude

TABLE 4. Calculated (at the B3LYP/6-311++G(2D,2P) Level) and Measured (in Various Solvents) Optical Rotations for Esters 4a, 4o, and 4p

ester	conformer	$[\alpha]_D$ calcd (deg)	$[\alpha]_D$ exp (deg)					
			$CHCl_3$	THF	Me_2CO	*i*-PrOH	EtOH	MeCN
4a	conf 1	−65						
	conf 2	+85						
	ΔG Boltzmann averaged	**−42**	**−4**	**−8**	**−3**	**−5**	**−2**	**+5**
4o	conf 1	−75						
	conf 2	−29						
	conf 3	−40						
	conf 4	−64						
	ΔG Boltzmann averaged	**−55**	**−27**	**−44**	**−13**	**−36**	**−24**	**−21**
4p	conf 1	−141						
	conf 2	−45						
	conf 3	−45						
	ΔG Boltzmann averaged	**−101**	**−35**	**−35**	**−24**	**−34**	**−27**	**−12**

of the exciton Cotton effect of **4p** contrasts with the reported data for malic acid di-2-naphthyl ester of the same (*R*) configuration ($A = +12.9$).[13] Interestingly, calculations show nearly canceling contributions of the rotatory strengths to the long-wavelength Cotton effect of **4o** and **4p**. This is in accordance with the experimentally observed small Cotton effect for naphthalene ^1L_a transition in these esters.

Finally, we calculated the optical rotations of individual conformers of aryl esters **4a**, **4o**, and **4p** (Table 4).

The two conformers of **4a** contribute rotations of opposite sign. Experimental small negative $[\alpha]_D$ values measured in various solvents (except in acetonitrile) agree qualitatively with the dominant contribution of conformer 1, characterized by a negative calculated $[\alpha]_D$. In the case of dinaphthyl esters **4o** and **4p** all calculated conformers are characterized by negative rotation; hence, the population-averaged calculated $[\alpha]_D$ agrees quite well with the negative $[\alpha]_D$ values for **4o** and **4p** measured experimentally in solvents ranging from chloroform to acetonitrile (Table 4).

In conclusion, the CD and $[\alpha]_D$ data for diaryl L-tartrate provide additional support for postulated preferred structures of these esters.

Conclusions

A series of diaryl L-tartrates have been synthesized and characterized for the first time. Despite their acyclic character, diaryl esters of L-tartaric acid have a rather rigid, extended structure as the result of conformational restrictions, mainly due to intramolecular vicinal hydrogen bonding between the O−H and C═O groups. Structure stabilizing 1,3-C═O/C−H dipole−dipole interactions seem to play additional role in determination of conformer population of diaryl L-tartrates. As a result, dinaphthyl L-tartrates display large exciton Cotton effects due to coupling of ^1B_b transitions, despite the distance between the two chromophores which exceeds 10.5 Å. It appears that 1-naphthyl chromophore until now remaining obscure is particularly well-suited for stereochemical studies with the use of CD spectroscopy, as it gives rise to much larger Cotton effects, compared to the commonly used 2-naphthyl chromophore. This consequently leads to the enhancement of sensitivity of CD measurements over large interchromophoric distances.

Experimental Section

Dimethyl 2,3-*O*-Benzylidene-L-tartrate (1). Compound **1** was prepared from dimethyl L-tartrate by a literature procedure:[14] yield 75%; mp 73−74 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.6−7.55 (m, 2H), 7.43−7.38 (m, 3H), 6.14 (s, 1H), 4.99 (d, 1H, $J = 4.1$ Hz), 4.88 (d, 1H, $J = 4.1$ Hz), 3.88 (s, 3H), 3.83 (s, 3H).

Disodium 2,3-*O*-Benzylidene-L-tartrate (2). The disodium salt was prepared by hydrolysis of compound **1** (3 g, 0.011 mol) by the addition of hot ethanol solution of NaOH (0.9 g in 20 mL) and stirring the mixture overnight at room temperature followed by concentration in vacuum. The oily white residue was then triturated with dry diethyl ether and stirred in an ice bath. The crystalline product **2** was filtered, washed with dry diethyl ether, and dried in vacuum (yield 3.06 g, 98%): ^{1}H NMR (300 MHz, D_2O) δ 7.68−7.64 (m, 2H), 7.54−7.48 (m, 3H), 6.05 (s, 1H), 4.70 (d, 1H, $J = 4.7$ Hz), 4.62 (d, 1H, $J = 4.7$ Hz).

Diaryl 2,3-*O*-Benzylidene-L-tartrates (3a−p). To a suspension of **2** (0.3 g, 1.1 mmol) in 2 mL of dry toluene containing one drop of DMF was added dropwise oxalyl chloride (1.2 mL) at 2−3 °C. After the reaction subsided, the mixture was refluxed at 65 °C for 2 h and then stirred overnight at room temperature. After evaporation of excess oxalyl chloride and the solvent under reduced pressure, dichloride **3** was obtained and immediately used for diester preparation without further purification.

To a solution of dichloride **3** in dry dichloromethane (5 mL) was added 2 equiv of phenol or naphthol, followed by dropwise addition of pyridine (0.4 mL) in dry dichloromethane (2 mL). After overnight stirring, the reaction mixture was extracted with 2 N HCl, and the organic layer was separated and washed twice with distilled water and then dried over Na_2SO_4. After filtration, the solvent was evaporated and the residue purified by radial chromatography on silica gel plates (2 mm thickness).

Diphenyl 2,3-*O*-benzylidene-L-tartrate (3a): yield 243 mg (57%); mp 77−79 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68−7.64 (m, 2H), 7.47−7.11(m, 13H), 6.35 (s, 1H), 5.39 (d, 1H, $J = 3.6$ Hz), 5.27 (d, 1H, $J = 3.6$ Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.9, 167.4, 150.1, 150.0, 135.2, 130.1, 129.6, 129.5, 128.4, 127.2, 126.5, 126.4, 121.3, 107.2, 77.6, 77.3; HRMS (*m*/*z*) 391.1218 [M + H] ($C_{23}H_{19}O_6H$, calcd 391.1182).

Bis(4-methylphenyl) 2,3-*O*-benzylidene-L-tartrate (3b): yield 265 mg (58%); mp 97−99 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.67−7.63 (m, 2H), 7.44−7.39 (m, 3H), 7.23−7.17 (m, 4H) 7.09−7.06 (m, 2H) 7.02−6.98 (m, 2H) 6.33 (s, 1H), 5.36 (d, 1H, $J = 3.8$ Hz), 5.24 (d, 1H, $J = 3.8$ Hz), 2.36 (s, 3H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.1, 167.6, 147.9, 147.8, 136.2, 136.1, 135.3, 130.15, 130.11, 130.0, 128.4, 127.2, 120.8, 120.7, 107.2, 77.7, 77.4, 20.89, 20.87; HRMS (*m*/*z*): 441.1316 [M + Na] ($C_{25}H_{22}O_6Na$, calcd 441.1314).

Bis(4-*tert*-butylphenyl) 2,3-*O*-benzylidene-L-tartrate (3c): yield 370 mg (67%); oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.67−7.63 (m, 2H), 7.45−7.38 (m, 7H), 7.14−7.02 (m, 4H), 6.34 (s, 1H), 5.37 (d, 1H, $J = 4.1$ Hz), 5.25 (d, 1H, $J = 4.0$ Hz), 1.33 (s, 9H), 1.32 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.0, 167.6, 149.4, 149.3, 147.8, 147.7, 135.3, 130.1, 128.4, 127.2, 126.5, 126.4, 120.43, 120.42, 107.2, 77.7, 77.4, 34.55, 34.52, 31.3; HRMS (*m*/*z*) 525.2302 [M + Na] ($C_{31}H_{34}O_6Na$, calcd 525.2253).

Bis(4-formylphenyl) 2,3-*O*-benzylidene-L-tartrate (3d): yield 146 mg (30%); mp 116−118 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.03 (s, 1H), 10.01 (s, 1H), 8.02−7.26 (m, 13H), 6.37 (s, 1H), 5.44 (d, 1H, $J = 3.8$ Hz), 5.31 (d, 1H, $J = 3.8$ Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 190.6, 167.2, 166.7, 154.5, 154.4, 134.9, 134.6, 134.5, 131.4, 131.3, 130.3, 128.6, 127.0, 122.0, 121.9, 107.4, 77.5, 77.2; HRMS (*m*/*z*) 447.1915 [M + H] ($C_{25}H_{18}O_8H$, calcd 447.1948).

Bis(2-bromophenyl) 2,3-*O*-benzylidene-L-tartrate (3e): yield 378 mg (60%); oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.70−7.61 (m, 4H), 7.44−7.32 (m, 5H), 7.26−7.13 (m, 4H), 6.39 (s, 1H), 5.66 (d, 1H, $J = 3.8$ Hz), 5.52 (d, 1H, $J = 3.6$ Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.1, 166.7, 147.5, 147.4, 134.9, 133.6, 133.5, 130.2, 128.8, 128.7, 128.4, 128.1, 128.0, 127.4, 123.4, 115.8, 115.7, 107.6, 77.7, 77.3; HRMS (*m*/*z*) 570.8700 [M + Na] ($C_{23}H_{16}Br_2O_6Na$, calcd 570.9211).

Bis(3-bromophenyl) 2,3-*O*-benzylidene-L-tartrate (3f): yield 315 mg (50%); mp 68−71 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.65−7.62 (m, 2H), 7.47−7.05 (m, 11H), 6.34 (s, 1H), 5.37 (d, 1H, J = 3.8 Hz), 5.22 (d, 1H, J = 3.7 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.4, 166.9, 150.4, 150.3, 135.0, 130.7, 130.6, 130.2, 129.8, 129.7, 128.5, 127.1, 124.66, 124.62, 122.6, 122.5, 120.0, 119.9, 107.3, 77.4, 77.1; HRMS (*m*/*z*) 570.8700 [M + Na] ($C_{23}H_{16}Br_2O_6Na$, calcd 570.9211).

Bis(4-bromophenyl) 2,3-*O*-benzylidene-L-tartrate (3g): yield 320 mg (53%); mp 118−120 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.64−7.40 (m, 9H), 7.12−6.96 (m, 4H), 6.33 (s, 1H), 5.36 (d, 1H, J = 3.8 Hz), 5.23 (d, 1H, J = 3.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.5, 167.0, 149.0, 148.9, 135.0, 132.7, 132.6, 130.2, 128.5, 127.1, 122.9, 122.8, 119.8, 119.6, 107.3, 77.5, 77.2; HRMS (*m*/*z*) 570.8611 [M + Na] ($C_{23}H_{16}Br_2O_6Na$, calcd 570.9211).

Bis(4-nitrophenyl) 2,3-*O*-benzylidene-L-tartrate (3h): yield 36% (190 mg); mp 157−159 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.37−8.27 (m, 4H), 7.64−7.61 (m, 2H), 7.48−7.40 (m, 5H), 7.29−7.25 (m, 2H), 6.37 (s, 1H), 5.45 (d, 1H, J = 3.6 Hz), 5.31 (d, 1H, J = 3.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$ + CD_3COCD_3) δ 167.0, 166.6, 154.6, 154.5, 145.99, 145.90, 134.9, 130.3, 128.6, 127.1, 125.5, 125.4, 122.3, 122.2, 107.4, 77.4, 77.1; HRMS (*m*/*z*) 481.1044 [M + H] ($C_{23}H_{16}N_2O_{10}H$, calcd 481.0883).

Bis(2,4-di-*tert*-butylphenyl) 2,3-*O*-benzylidene-L-tartrate (3i): yield 347 mg (52%); mp 49−52 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68−7.64 (m, 2H), 7.44−7.39 (m, 5H), 7.29 (d, 1H, J = 2.4 Hz), 7.22 (d, 1H, J = 2.4 Hz), 7.01 (d, 1H, J = 8.3 Hz), 6.92 (d, 1H, J = 8.3 Hz), 6.35 (s, 1H), 1.38 (s, 9H), 1.34 (s, 9H), 1.33 (s, 9H), 1.31 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.4, 167.7, 148.9, 148.8, 146.4, 146.3, 140.0, 135.0, 130.0, 128.4, 127.2, 124.4, 124.3, 124.0, 123.9, 122.6, 107.2, 77.8, 77.5, 34.73, 34.71, 31.6, 31.4, 30.34, 30.31; HRMS (*m*/*z*) 637.3516 [M + Na] ($C_{39}H_{50}O_6Na$, calcd 637.3505).

Bis(2,4-dichlorophenyl) 2,3-*O*-benzylidene-L-tartrate (3j): yield 220 mg (38%); mp 109−111 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.66−7.08 (m, 11H), 6.35 (s, 1H), 5.54 (d, 1H, J = 3.6 Hz), 5.41 (d, 1H, J = 3.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.8, 166.3, 144.9, 144.8, 134.7, 132.8, 132.7, 130.39, 130.33, 130.31, 128.5, 128.3, 128.2, 127.56, 127.50, 127.3, 124.24, 124.22, 107.6, 77.5, 76.9; HRMS (*m*/*z*) 550.8944 [M + Na] ($C_{23}H_{14}Cl_4O_6Na$, calcd 550.9442).

Bis(2,4-dibromo-6-*tert*-butoxycarbonylphenyl) 2,3-*O*-benzylidene-L-tartrate (3k): yield 540 mg (54%); mp 84−86 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.00−7.90 (m, 4H), 7.71−7.68 (m, 2H), 7.42−7.37 (m, 3H), 6.37 (s, 1H), 5.92 (d, 1H, J = 3.3 Hz), 5.72 (d, 1H, J = 3.3 Hz), 1.56 (s, 9H), 1.54 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 166.4, 161.3, 146.4, 146.3, 139.7, 138.96, 138.91, 135.1, 133.5, 133.4, 130.0, 129.8, 128.3, 127.6, 119.8, 119.6, 119.1, 119.0, 107.5, 77.0, 76.4, 33.6, 28.03, 28.01; HRMS (*m*/*z*) 928.8531 [M + Na] ($C_{33}H_{30}Br_4O_{10}Na$, calcd 928.8470).

Bis[2-(phenoxycarbonyl)phenyl] 2,3-*O*-benzylidene-L-tartrate (3l): yield 400 mg (43%); mp 43−45 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.27−8.21 (m, 2H), 7.67−7.09 (m, 21H), 6.20 (s, 1H), 5.66 (d, 1H, J = 3.7 Hz), 5.52 (d, 1H, J = 3.7 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.1, 167.7, 162.65, 162.62, 150.4, 150.36, 150.30, 135.3, 134.7, 134.6, 132.2, 132.1, 129.9, 129.5, 129.4, 128.2, 127.4, 126.7, 126.6, 126.08, 126.02, 123.73, 123.71, 122.49, 122.44, 121.66, 121.62, 106.9, 77.2, 76.6; HRMS (*m*/*z*) 653.0815 [M + Na] ($C_{37}H_{26}O_{10}Na$, calcd 653.1424).

Bis[4-(methoxycarbonyl)phenyl] 2,3-*O*-benzylidene-L-tartrate (3m): yield 322 mg (58%); mp 104−106 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.15−8.07 (m, 4H), 7.66−7.63 (m, 2H), 7.45−7.42 (m, 3H), 7.30 (dd, 2H, J = 2.0, 6.8 Hz), 7.19 (dd, 2H, J = 2.0, 6.8 Hz), 6.35 (s, 1H), 5.41 (d, 1H, J = 3.8 Hz), 5.28 (d, 1H, J = 3.8 Hz), 3.93 (s, 3H), 3.92 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$ + CD_3COCD_3) δ 167.4, 166.9, 166.09, 166.08, 153.6, 153.5, 135.1 131.8, 131.4, 131.3, 130.2, 128.5, 128.4, 127.1, 121.29, 121.23, 107.3, 77.5, 77.2, 52.34, 52.31; HRMS (*m*/*z*) 529.1226 [M + Na] ($C_{27}H_{22}O_{10}Na$, calcd 529.1111).

Bisi(4-biphenyl) 2,3-*O*-benzylidene-L-tartrate (3n): yield 211 mg (43%); mp 201−203 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.70−7.18 (m, 23H), 6.38 (s, 1H), 5.44 (d, 1H, J = 3.8 Hz), 5.31 (d, 1H, J = 3.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.0, 167.5, 149.5, 149.4, 140.1, 140.0, 139.8, 139.7, 135.2, 130.1, 128.88, 128.86, 128.7, 128.5, 128.4, 128.3, 127.59, 127.55, 127.2, 127.1, 121.43, 121.40, 107.3, 77.7, 77.4; HRMS (*m*/*z*): 565.1848 [M + Na] ($C_{35}H_{26}O_6Na$, calcd 565.1627).

Bis(1-naphthyl) 2,3-*O*-benzylidene-L-tartrate (3o): yield 250 mg (47%); mp 124−126 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.00−7.72 (m, 8H), 7.57−7.34 (m, 11H), 6.49 (s, 1H), 5.70 (d, 1H, J = 4.1 Hz), 5.59 (d, 1H, J = 4.1 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.1, 167.4, 145.9, 145.8, 135.1, 134.7, 134.6, 130.2, 128.5, 128.1, 128.0, 127.3, 126.9, 126.8, 126.7, 126.6, 126.5, 126.3, 126.2, 125.3, 125.2, 120.8, 120.7, 117.8, 117.7, 107.5, 77.9, 77.7; HRMS (*m*/*z*) 513.1382 [M + Na] ($C_{31}H_{22}O_6Na$, calcd 513.1314).

Bis(2-naphthyl) 2,3-*O*-benzylidene-L-tartrate (3p): yield 280 mg (57%); mp 141−143 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.93−7.24 (m, 19H), 6.42 (s, 1H), 5.51 (d, 1H, J = 3.8 Hz), 5.39 (d, 1H, J = 3.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.1, 167.6, 147.7, 147.6, 135.2, 133.63, 133.61, 131.7, 131.6, 130.1, 129.8, 129.7, 128.5, 127.85, 127.81, 127.75, 127.73, 127.2, 126.9, 126.8, 126.1, 126.0, 120.3, 118.4, 118.3, 107.3, 77.7, 77.5; HRMS (*m*/*z*) 513.1225 [M + Na] ($C_{27}H_{22}O_{10}Na$, calcd 513.1314).

Diaryl L-Tartrates (4a−p). A sample of acetal **3a−p** (50 mg) was dissolved in 2 mL of dry dichloromethane and stirred with a TFA/H_2O mixture (8:2, 0.2 mL) for 30−90 min depending on the compound used (TLC control). The solution was then washed three times with distilled water, and the organic layer was dried over anhydrous Na_2SO_4. After evaporation, the residue was purified by radial chromatography. The esters **4a−p** were further purified by crystallization from a minimum amount of hot hexane/ethyl acetate or dichloromethane/methanol.

Diphenyl L-tartrate (4a): yield 35 mg (90%); mp 159−162 °C; $[\alpha]_D^{20}$ −2.8 (c = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) δ 7.49−7.42 (m, 4H), 7.32−7.27 (m, 2H), 7.23−7.19 (m, 4H), 5.10 (s, 2H), 4.98 (s, 2H); ^{13}C NMR (75 MHz, CD_3COCD_3) δ 170.5, 151.5, 130.1, 126.6, 122.2, 73.8; EI-MS (*m*/*z*) 302.1 [M^+], 274.0, 181.1, 135.0, 94.0; HRMS (*m*/*z*) 325.0670 [M + Na] ($C_{16}H_{14}O_6Na$, calcd 325.0688). Crystals suitable for X-ray crystallography were grown from saturated dichloromethane/methanol solution.

Bis(4-methylphenyl) L-tartrate (4b): yield 34 mg (79%); mp 154−156 °C; $[\alpha]_D^{20}$ −8.8 (c = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) δ 7.25−7.22 (m, 4H), 7.08−7.05 (m, 4H), 5.06 (s, 2H), 4.87 (s, 2H), 2.33 (s, 6H); ^{13}C NMR (75 MHz, CD_3COCD_3) δ 170.6, 149.3, 136.1, 130.5, 121.9, 73.7, 20.7; FAB-MS (NBA matrix) (*m*/*z*) 330.9 [M + H]; HRMS (*m*/*z*) 353.0993 [M + Na] ($C_{18}H_{18}O_6Na$, calcd 353.1001).

Bis(4-*tert*-butylphenyl) L-tartrate (4c): yield 38 mg (92%); mp 127−130 °C; $[\alpha]_D^{20}$ −8.4 (c = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) δ 7.50−7.45 (m, 4H), 7.15−7.10 (m, 4H), 5.08 (s, 2H), 4.93 (s, 2H), 1.33 (s, 18H); ^{13}C NMR (75 MHz, CD_3COCD_3) δ 170.6, 149.3, 149.2, 126.9, 121.6, 73.7, 34.9, 31.6; FAB-MS (*m*/*z*) 437.2 [M + Na], 415.2 [M + H]; HRMS (*m*/*z*) 437.1823 [M + Na] ($C_{24}H_{30}O_6Na$, calcd 437.1940).

Bis(4-formylphenyl) L-Tartrate (4d). In this reaction, acetonitrile was used as solvent instead of dichloromethane: yield 32 mg (80%); mp 126−129 °C; $[\alpha]_D^{20}$ −20.6 (c = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) δ 10.06 (s, 2H), 8.07−8.02 (m, 4H), 7.48−7.43 (m, 4H), 5.20 (s, 4H); ^{1}H NMR (300 MHz, CD_3COCD_3 + D_2O) δ 10.06 (s, 2H), 8.07−8.03 (m, 4H), 7.49−7.46 (m, 4H), 5.19 (s, 2H); ^{13}C NMR (75 MHz, CD_3COCD_3) δ 191.4, 170.0, 155.8, 135.3, 131.6, 123.1, 73.8; ESI-MS (*m*/*z*) 359 [M + H]; HRMS (*m*/*z*) 381.0377 [M + Na] ($C_{18}H_{14}O_8Na$, calcd 381.0586).

Bis(2-bromophenyl) L-tartrate (4e): yield 33 mg (78%); mp 109−111 °C; $[\alpha]_D^{20}$ −29.2 (c = 0.5, acetone); ^{1}H NMR (400 MHz, CD_3COCD_3) δ 7.74 (dd, 2H, J = 1.4, 8.6 Hz), 7.51−7.45 (m, 2H), 7.36−7.25 (m, 4H), 5.26 (s, 2H); ^{13}C NMR (100 MHz, CD_3COCD_3) δ 169.8, 148.9, 134.2, 129.7, 128.7, 124.9, 116.3, 73.6; ESI-MS

(*m*/*z*) 483 [Na^+]; HRMS (*m*/*z*) 482.8963 [M + Na] ($C_{16}H_{12}Br_2O_6Na$, calcd 482.8898).

Bis(3-bromophenyl) L-tartrate (4f): yield 34 mg (81%); mp 140−142 °C; $[\alpha]_D^{20}$ −5.4 (*c* = 0.5, acetone); ^{1}H NMR (400 MHz, CD_3COCD_3) *δ* 7.53 (m, 6H), 7.27 (m, 2H), 5.14 (s, 2H); ^{13}C NMR (100 MHz, CD_3COCD_3) *δ* 170.4, 152.3, 131.9, 129.9, 125.7, 122.5, 121.6, 73.8; ESI-MS (*m*/*z*) 483 [M + Na^+]; HRMS (*m*/*z*) 482.9044 [M + Na] ($C_{16}H_{12}Br_2O_6Na$, calcd 482.8898).

Bi(4-bromophenyl) L-tartrate (4g): yield 32 mg (76%); mp 196−199 °C; $[\alpha]_D^{20}$ −4.2 (*c* = 0.5, DMSO); ^{1}H NMR (300 MHz, DMSO) *δ* 7.67 (d, 4H, *J* = 8.6 Hz), 7.15 (d, 4H, *J* = 8.6 Hz), 6.21 (d, 2H, *J* = 7.8 Hz), 4.97 (d, 2H, *J* = 7.7 Hz); ^{13}C NMR (75 MHz, DMSO) *δ* 169.5, 149.3, 132.3, 123.7, 118.1, 72.5; EI-MS (*m*/*z*): 459.9 [M^+], 431.9, 382.9, 251.8, 174, 171.9; HRMS (*m*/*z*) 482.9044 [M + Na] ($C_{16}H_{12}Br_2O_6Na$, calcd 482.8898).

Bis(4-nitrophenyl) L-tartrate (4h): yield 34 mg (83%); mp 144−146 °C; $[\alpha]_D^{20}$ −24.4 (*c* = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) *δ* 8.40−8.34 (m, 4H), 7.56−7.48 (m, 4H), 5.36 (d, 2H, *J* = 7.9 Hz), 5.27 (d, 2H, *J* = 6.8 Hz); ^{13}C NMR (75 MHz, CD_3COCD_3) *δ* 169.7, 156.1, 146.4, 125.9, 123.4, 73.8; EI-MS (*m*/*z*) 392.9 [M^+], 363.9, 277.9, 226.0, 139.1; HRMS (*m*/*z*) 415.0533 [M + Na] ($C_{16}H_{12}N_2O_{10}Na$, calcd 415.0390).

Bis(2,4-di-*tert*-butylphenyl) L-tartrate (4i): yield 34 mg (80%); mp 72−74 °C; $[\alpha]_D^{20}$ −12.5 (*c* = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) *δ* 7.49 (d, 2H, *J* = 2.4 Hz), 7.32 (dd, 2H, *J* = 2.4, 8.4 Hz), 7.05 (d, 2H, *J* = 8.4 Hz), 5.17 (dd, 2H, *J* = 1.4, 7.0 Hz), 5.07 (dd, 2H, *J* = 1.4, 7.0 Hz), 1.39 (s, 18H), 1.33 (s, 18H); ^{13}C NMR (75 MHz, CD_3COCD_3) *δ* 170.8, 148.8, 147.9, 140.7, 124.5, 124.4, 123.9, 74.0, 35.25, 35.20, 31.7, 30.6; EI-MS (*m*/*z*) 526.2 [M^+], 498.2, 305.0, 219.0, 206.1, 191.1, 57.1; HRMS (*m*/*z*) 549.3257 [M + Na] ($C_{32}H_{46}O_6Na$, calcd 549.3192).

Bis(2,4-dichlorophenyl) L-tartrate (4j): yield 34 mg (82%); mp 87−89 °C; $[\alpha]_D^{20}$ −23.6 (*c* = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) *δ* 7.67 (d, 2H, *J* = 2.6 Hz), 7.51 (dd, 2H, *J* = 2.4, 8.7 Hz), 7.39 (d, 2H, *J* = 8.6 Hz) 5.25 (s, 4H);^{13}C NMR (75 MHz, CD_3COCD_3) *δ* 169.3, 146.4, 132.4, 130.4, 129.0, 128.2, 125.9, 73.5; ESI-MS (*m*/*z*) 441.0 [M + H]; FAB-MS (*m*/*z*) 440.9 [M + H]; HRMS (*m*/*z*) 462.9129 [M + Na] ($C_{16}H_{10}Cl_4O_6Na$, calcd 463.1546).

bis(2,4-dibromo-6-*tert*-butoxycarbonylphenyl) L-tartrate (4k): yield 40 mg (89%); mp 173−175 °C; ^{1}H NMR (300 MHz, CD_3COCD_3) *δ* 8.16 (d, 2H, *J* = 2.5 Hz), 8.08 (d, 2H, *J* = 2.5 Hz), 5.38 (d, 2H, *J* = 8.6 Hz), 5.14 (d, 2H, *J* = 8.6 Hz), 1.59 (s, 18H); ^{13}C NMR (75 MHz, CD_3COCD_3) *δ* 169.2, 162.38, 147.2, 139.6, 134.1, 129.5, 120.0, 119.8, 84.0, 73.2, 28.0; FAB-MS (*m*/*z*) 841.0 [M + $Na]^+$; HRMS (*m*/*z*) 840.8405 [M + Na] ($C_{26}H_{26}Br_4O_{10}Na$, calcd 840.8157).

Bis(2-phenoxycarbonylphenyl) L-tartrate (4l): yield 22 mg (51%); mp 39−41 °C; $[\alpha]_D^{20}$ −84.4 (*c* = 0.5, acetone); ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 8.28 (dd, 2H, *J* = 1.4, 7.6 Hz), 7.69−7.63 (m, 2H), 7.45−7.35 (m, 6H), 7.27−7.14 (m, 8H) 5.20 (s, 2H), 3.51 (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 169.5, 162.6, 150.4, 150.1, 134.8, 132.1, 129.4, 126.6, 126.0, 123.9, 121.9, 121.5, 72.4; FAB-MS (*m*/*z*) 542.9 [M + H]; HRMS (*m*/*z*) 565.0963 [M + Na] ($C_{30}H_{22}O_{10}Na$, calcd 565.1111).

Bis(4-methoxycarbonylphenyl) L-Tartrate (4m). In this reaction, acetonitrile was used as solvent instead of dichloromethane: yield 27 mg (65%); mp 199−201 °C; $[\alpha]_D^{20}$ −46.8 (*c* = 0.5, DMSO); ^{1}H NMR (300 MHz, DMSO) *δ* 8.09−8.04 (m, 4H), 7.34−7.30 (m, 4H), 6.28 (d, 2H, *J* = 8.0 Hz), 5.03 (d, 2H, *J* = 7.8 Hz), 3.87 (s, 6H); ^{1}H NMR (300 MHz, DMSO + D_2O) *δ* 8.01−8.05 (m, 4H), 7.36−7.31 (m, 4H), 5.03 (s, 2H), 3.87 (s, 6H); ^{13}C NMR (75 MHz, DMSO) *δ* 169.3, 165.2, 153.8, 130.7, 127.2, 121.9, 72.5, 52.2; EI-MS (*m*/*z*) 418.9 [M^+], 390.0, 327.1, 239.0, 152.0, 121.0, 93.0; HRMS (*m*/*z*) 441.0798 [M + Na] ($C_{20}H_{18}O_{10}Na$, calcd 441.0827).

Di(4-biphenyl) L-Tartrate (4n). The reaction was carried out without dichloromethane as cosolvent: yield 30 mg (72%); mp 262−265 °C; $[\alpha]_D^{20}$ −23.4 (*c* = 0.5, DMSO); ^{1}H NMR (300 MHz, DMSO) *δ* 7.76 (d, 4H, *J* = 7.6 Hz), 7.70 (d, 4H, *J* = 7.6 Hz), 7.51 (t, 4H, *J* = 7.2 Hz), 7.40 (t, 2H, *J* = 7.2 Hz) 7.27 (d, 4H, *J* = 7.6 Hz), 6.21 (d, 2H, *J* = 7.0 Hz), 5.02 (d, 2H, *J* = 6.8 Hz); ^{13}C NMR (75 MHz, DMSO) *δ* 169.8, 149.6, 139.0, 137.7, 128.7, 127.6, 127.3, 126.5, 121.8, 72.6; EI-MS (*m*/*z*) 454.0 [M^+], 420.0, 284.0, 250.9, 170.0, 141.0; HRMS (*m*/*z*) 477.1676 [M + Na] ($C_{28}H_{22}O_6Na$, calcd 477.1314).

Di(1-naphthyl) L-tartrate (4o): yield 33 mg (80%); mp 42−47 °C; $[\alpha]_D^{20}$ −12.7 (*c* = 0.5, acetone); ^{1}H NMR (300 MHz, CD_3COCD_3) *δ* 8.27−8.23 (m, 2H), 8.02−7.94 (m, 2H), 7.90 (d, 2H, *J* = 8.2 Hz) 7.62−7.54 (m, 6H), 7.42 (dd, 2H, *J* = 1.0, 7.5 Hz), 5.57 (d, 2H, *J* = 7.0 Hz), 5.34 (d, 2H, *J* = 7.0 Hz); ^{1}H NMR (300 MHz, CD_3COCD_3 + D_2O) *δ* 8.25−8.22 (m, 2H), 8.02−7.99 (m, 2H), 7.92 (d, 2H, *J* = 8.2 Hz) 7.62−7.56 (m, 6H), 7.44 (d, 2H, *J* = 7.4 Hz) 5.52 (s, 2H); ^{13}C NMR (75 MHz, CD_3COCD_3) *δ* 170.7, 147.5, 135.4, 128.5, 127.6, 127.29, 127.22, 126.9, 126.2, 122.4, 118.9, 74.1; EI-MS (*m*/*z*) 402.1 [M^+], 374.1, 268.9, 185.1, 144.0, 115.1; HRMS (*m*/*z*) 425.1126 [M + Na] ($C_{24}H_{18}O_6Na$, calcd 425.1001).

Di(2-naphthyl) L-tartrate (4p): yield 35 mg (85%); mp 196−198 °C; $[\alpha]_D^{20}$ −23.8 (*c* = 0.5, acetone); ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 7.93−7.83 (m, 6H), 7.68 (d, 2H, *J* = 2.3 Hz), 7.54−7.50 (m, 4H) 7.34 (dd, 2H, *J* = 2.4, 8.8 Hz), 5.16 (s, 2H); ^{1}H NMR (300 MHz, CD_3COCD_3 + D_2O) *δ* 8.04−7.93 (m, 6H), 7.76 (d, 2H, *J* = 2.2 Hz), 7.61−7.52 (m, 4H) 7.43 (dd, 2H, *J* = 2.2, 8.8 Hz), 5.23 (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 170.3, 147.8, 133.6, 131.7, 129.8, 127.8, 127.7, 126.8, 126.1, 120.3, 118.4, 72.5; EI-MS (*m*/*z*) 402.2 [M^+], 374.0, 269.0, 185.1, 144.0, 115.0; HRMS (*m*/*z*) 425.1203 [M + Na] ($C_{24}H_{18}O_6Na$, calcd 425.1001).

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Supporting Information Available: Crystallographic data (CIF), computational details, Cartesian coordinates for all calculated structures, CD and UV spectra calculated at the B3LYP/6-311++G(2D,2P) level, and copies of ^{1}H and ^{13}C NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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