this is in support of the mechanistic proposal according to which 3-fluoroanisole undergoes kinetic lithiation at C_2 because it is capable of acting as "a pair of tweezers" (F–O distance = 4.780 Å) upon a lithium dimer having two coordinatively unsaturated lithium atoms. Again, this preference can be traced down to the strength of the five large neighbor interactions present in $TS_{6c\text{-}C2}$.

In summary, we have presented convincing theoretical (MNDO) evidence for the intermediate formation of weak, bidentate (chelated) complexes in the lithiation of some representative 1,3-disubstituted heteroatom aromatics. This bidentate coordination ("pair of tweezers") mechanism qualitatively explains both the kinetic acceleration (dynamic molecular recognition)[44] and the regioselective hydrogen abstraction at C_2–H experimentally observed. Chelated complexes, which are true local minima on the energy surfaces, show intense C_2–H agostic interactions in spite of the fact that both lithium atoms are formally pentacoordinated. Remarkably, MNDO shows that lithiation by the monocoordination mode at C_6 is favored over that at C_2 for DMB and DFB, because they are entropy-controlled reactions. For enthalpy-controlled reactions, a subtle interplay between neighbor and non-neighbor interactions actually determines the outcome of the lithiation of prototype 1,3-disubstituted aromatics. In particular, by partitioning the MNDO-calculated transition state energy, it can be realized that lithiation at C_2 by the bidentate coordination mode is favored over lithiation by the monodentate coordination mode at either C_2 or C_6 largely because the strength of neighbor interactions is larger through the former route.

We hope these results might help in defining novel ditopic or polytopic chelators for complex bases involving either lithium or other metals. As suggested by Jorgensen's mnemonics for binding between neutral compounds, central criteria for success should be that attractive forces are maximized whereas repulsive ones are minimized.

Acknowledgment. Time allocation for calculations was generously provided by the Centre de Càlcul de la Universitat de les Illes Balears. Financial support by the DGICYT (PB90-0040) is gratefully acknowledged. We are indebted to Professor S. Olivella (U. de Barcelona, Spain) for valuable suggestions and comments during the course of our work, as well as for making his modified version of MOPAC available to us, and to Dr. A. Costa and P. Ballester for helpful discussions.

Registry No. 1a, 151-10-0; **1b**, 372-18-9; **1c**, 456-49-5; $[CH_3Li(H_2O)_2]_2$, 143631-78-1.

Supplementary Material Available: Tables of Cartesian coordinates of the optimized molecular structures (22 pages). Ordering information is given on any current masthead page.

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Computational Evaluation of the Coupled Oscillator Model in the Vibrational Circular Dichroism of Selected Small Molecules

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Abstract: A comparison is made between the predictions of the dynamic coupling or coupled oscillator model of vibrational circular dichroism (VCD) and those of the a priori magnetic field perturbation (MFP) theory as formulated by Stephens. For two independent formaldehyde molecules at reasonably large separations, both calculations are in agreement for the C=O VCD; but deviations develop at short separations. In addition, calculated results for seven different cyclopropane- or cyclobutane-based molecules made chiral by trans-dideuterio substitution are presented. For identical C–H and C–D stretch oscillators, the hydrocarbons studied gave MFP computed VCD spectra that are qualitatively predictable with the coupled oscillator model, but the MFP magnitudes were uniformly larger and exhibited a progressive degree of inequality. However, the coupled oscillator model failed for some oxygen-containing molecules studied, implying that its application is far from universal.

Introduction

The simplest model for vibrational circular dichroism (VCD) is known variously as the dynamic coupling, exciton coupling, or degenerate coupled oscillator (DCO) mechanism,[1,2] whereby monomer-like excitations of local transition dipoles are mixed to form properly phased molecular excitations. Effects of dipolar mixing are most evident for degenerate oscillators, those related by a symmetry operation, but dynamic coupling can contribute to the VCD of any pair of oscillators. If these degenerate local oscillators are non-coplanar, a VCD spectrum results which has a positive and a negative lobe of the same intensity (often termed a "conservative couplet") that usually result in a characteristic derivative shape whose intensity and sign is dependent on the relative angle between the oscillators and consequently on the geometry of the molecule.

Over the last 15 years, a number of reported VCD spectra, especially for C_2 symmetry molecules, have evidenced such band shapes.[3-5] Consequently, with some success, efforts have been

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made to interpret these spectra using the coupled oscillator formalism.[3,6-8] However, a number of symmetrical molecules yield VCD spectra that are not interpretable with this simple model. Perhaps the simplest example of this failure is that of the cyclobutanedione VCD we reported recently.[9] In that case the C–H and C–D stretches would appear to be appropriate examples of the coupled oscillator mechanism, but the VCD spectra observed in both spectral regions are of a single sign. This and other exceptions have made the applicability of the coupled oscillator model limited and have further added to the desire of spectroscopists and stereochemists for more general methods of calculation of VCD spectra.

Emphasis in theoretical analysis of VCD has thus shifted over the last decade to more complex and general methods of calculation of VCD, with the most reliable results coming from quantum mechanical calculation of the electric and magnetic transition moments at the ab initio level.[10] However, in recent years, a renewed interest in the DCO model of VCD has developed first with regard to polymeric molecules, especially DNAs,[7,11] and most recently as a method of analysis of selected regions (modes composed primarily of stretches of similar bonds) of the VCD spectra of simple small molecules.[12] It is these latter applications along with our continuing investigations of C_2 symmetry molecules made chiral by isotopic substitution[9,13-15] that prompt this study. We will use the results of a calculative exercise comparing the coupled oscillator mechanism with more reliable ab initio calculations to explore the types of systems for which the DCO model is applicable and those for which it is not.

Our reference ab initio based computations use an a priori magnetic field perturbation (MFP) method developed and applied by Stephens and co-workers[16,17] for computing VCD intensities. While not the only method using ab initio quantum mechanical computations,[18-20] the MFP approach has come to dominate efforts aimed at general analysis of VCD spectra of small molecules. For those molecules studied, this method has shown repeated success, particularly when larger, split-valence basis sets are used and the Hartree–Fock limit is approached. However, the costs of this success are high due to the relatively high quality of ground-state wave function needed to get reasonable agreement between calculation and experiment.

For many stereochemical applications of VCD, precision is not necessarily required. Determination of the sign and relative magnitude of several distinctive VCD bands with a reliable theoretical method would be sufficient to answer usefully a number of questions. This, of course, prompts one to reinvestigate the reliability of simpler models for computing VCD. Can one determine which molecules do give spectra that are at least qualitatively represented by a given simple model? Thus the question we address in this preliminary comparison of the results of the simple dynamic coupling model and the more accurate ab initio MFP method is one of reliability for the simple model. Our choice of ab initio models was based on convenience and tested applicability.

Computational Methods and Model Dimer Results

For a number of small molecules made chiral by isotopic substitution, we have calculated ab initio quantum mechanical force fields and atomic axial and polar tensors using the coupled Hartree–Fock methods of Amos and Stephens[16] as implemented in the program CADPAC version 4.0.[21] These tensors were combined with the atomic displacements using the distributed origin gauge with origins at the nuclei method of Stephens[16] to generate dipolar (D^k) and rotational (R^k) strengths for the transitions of interest. For this study we have focused on coupled C–H and C–D stretching motions. We report here the D^k and R^k values for the modes which evidence the largest contribution from the symmetric (in phase) and antisymmetric (out of phase) coupling of such local motions. For C–H and C–D stretches, the mixing with other local modes is relatively limited as indicated by the normal modes generated from our force fields. Use of such a group-frequency notation and comparison to the even simpler modes that result from the DCO model is thus a reasonable approximation for these modes. Most of the examples we will discuss here deal with modes formed from unique local oscillators related by a C_2 symmetry operation.

Our coupled oscillator (DCO) calculations follow the formalism of Holzwarth and Chabay[1] but use the computed minimum energy geometry and dipole strengths as derived from the above described ab initio calculations. For the sake of comparison, we have arbitrarily located the transition dipoles at the center of the C–H or C–D bonds and oriented them (a) along the bond axes and (b) along the ab initio computed directions as determined from

$$\vec{\mu}_{\mathrm{CH}} = (\vec{\mu}_{\mathrm{a}} + \vec{\mu}_{\mathrm{s}})/\sqrt{2} \qquad (1)$$

where $\vec{\mu}_a$ and $\vec{\mu}_s$ are the antisymmetric and symmetric *vectorial* dipole moments (from the CADPAC output) and μ_{CH} is the local CH dipole for the coupling of two CH stretches. The main problem in applying the coupled oscillator mechanism to analysis of VCD spectra is the determination of the sign and magnitude of the frequency splitting between the in- and out-of-phase modes. We have calculated the electrostatic dipolar coupling energy that has sometimes been used for this purpose and here compare it to the frequency splitting predicted by the ab initio force field.

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Table I. Coupled C=O Stretch VCD in Two Formaldehyde Molecules

(a) Torsion Angle O=C···C=O 20°

							DCO orientation					
	MFP result[c]						ab initio		along bonds			
dist[a]	ΔE^b	R^+	R^-	D^+	D^-	α^d	ΔE_d	R^+_d	ΔE_b	R^+	D^+	D^-
10	0.28	−314	314	558	17	<0.1	0.3	−313	0.3	−313	558	17
5	2.21	−153	156	533	16	0.2	2.1	−150	2.1	−149	533	17
3	12.19	−84	92	468	16	2.3	8.4	−82	8.4	−78	470	15

(b) Torsion Angle O=C···C=O 90°

							DCO orientation				
	MFP result[c]						ab initio		along bonds		
dist[a]	ΔE^b	R^+	R^-	D^+	D^-	α^d	ΔE_d	R^+_d	ΔE_b	R^+	D^+
10	−0.002	−922	921	289	288	0.25	0.003	−918	0.003	−918	288
5	−0.01	−463	458	283	279	0.28	0.1	−448	0.1	−447	281
3	0.36	−308	254	279	253	2.31	1.1	−257	1.0	−254	266
2	−22.83	−361	277	305	274	4.60	11.0	−173	6.4	−182	290

[a] Distance in Å between the two formaldehyde planes. [b] The energy difference in cm^{-1} between symmetric and antisymmetric modes. [c] The rotational strengths (R^+ for symmetric and R^- for antisymmetric) in 10^{-44} (esu·cm)^2 and dipole strengths in 10^{-40} (esu·cm)^2. [d] Angle between the bond and a priori uncoupled dipole moment in deg.

As an example of the continuity between these two methods of computing VCD, we have calculated the VCD for two formaldehyde molecules oriented with their planes parallel but held at 10 Å apart and twisted so that the C=O groups have a 20° torsion angle with the carbons placed on a line normal to the molecular planes. This "weakly bound" dimer has C_2 symmetry and must give rise to a VCD spectrum of some magnitude, at least. To carry out the a priori MFP calculation, the geometry of a single formaldehyde was first energy optimized using the 6-31G** basis set. Then two identical formaldehyde molecules were constrained to the described geometry, and the force field, normal mode frequencies, and atomic polar and atomic axial tensors of the dimer were calculated with the same basis set. Test calculations showed that optimization with a fixed torsion angle and separation distance for both formaldehyde molecules gives qualitatively the same results, of course, at a greater computational cost.

In the tables are presented the computed energies of the two coupled transitions as determined from the force field (ΔE) and from dipolar coupling (ΔE_d, along the ab initio dipole orientations, and ΔE_b, along the bond orientation)[2] along with the rotational strengths (R^+ and R^-) and dipole strengths (D^+ and D^-) from the MFP calculations. These are compared to the DCO rotational strengths computed with the atomic polar tensor orientation of the dipoles (R^+_d) and the bond orientation (R^+_b). The point dipoles were located at the center of the C=O bonds.

As shown in Table I, the two computations are in virtually perfect agreement under conditions for which the DCO model should be ideal. At 10-Å separation between the formaldehydes, the rotational strengths obtained for the in- and out-of-phase modes with the two calculations agree to within 0.5%, and the splitting of the transitions agrees to within 2%. When the formaldehyde molecules are brought closer, the $R^\pm$ (MFP) results begin to differ in magnitude and to have higher absolute values than predicted by the DCO calculations. In each calculation, the $R^\pm$ value decreases with decreasing separation while the ΔE value increases. The result of these opposing tendencies is that the couplet shaped VCD signal increases with decreasing separation (as determined from test plots of realistic band shapes). For comparison, the R^+_b values (dipoles oriented along the bonds) are always smaller than the R^+_d values (oriented in the atomic polar tensor orientation), with the R^+_d values falling between the MFP and the R^+_b values.

A second set of equivalent accuracy calculations was made using a relative angle of 90° between the C=O groups of the formaldehydes. As expected from the DCO formulas, the $R^\pm$ values were higher for this set of calculations than for the set with 20° orientation, but the ΔE values were near zero so the resultant VCD signals would be predicted to be very small. The same trends with decrease of separation of the monomers were found at this angle as with the smaller value. The MFP $R^\pm$ values are of greater magnitude than the DCO R^+_d values, with the MFP $R^\pm$ values being close to the DCO R^+_d values for large separations. These calculations are summarized in Table I.

In summary, these test calculations demonstrate that the simple DCO model does have a legitimate basis if used within its proposed assumptions. At the limit of low intermode interaction, the DCO result for local modes is in good agreement with the MFP results determined for the ab initio normal modes. If the previous success of Stephens's MFP model can be used as a guide, this would imply that the DCO model would also be successful for modeling VCD of weakly interacting vibrational modes in comparison with experiment. It is within such a realm that the applications of the DCO model to DNA are being undertaken.[11]

Single Molecule Results

The real problem with utilizing the coupled oscillator model arises when the oscillators are not ideally separated in space but are instead part of the same molecule being covalently bound. Then interactions other than dipolar, such as mechanical coupling and the need to meet the Sayvetz conditions,[8] can complicate the picture. Recently, interpretation of the VCD of d_2-cyclopropane has been postulated using an "extended coupled oscillator" approach.[12] Previously, C–H and C–D spectra for d_2-ethylene oxide were reported that appeared to derive from a coupled oscillator mechanism.[6] It has been demonstrated that these patterns also arise from high-level calculations,[20,22-25] but here we show by calculational exercise that, for more functionally complicated molecules, the DCO model is inapplicable. The molecules for which we have calculated spectra are illustrated in Figure 1.

Three-Membered Rings. We have calculated VCD for these already studied molecules and for some other systems of our own design using both Stephens's a priori MFP and the DCO methods. The three-membered ring compounds include: (**1**) (1*S*,2*S*)-dideuteriocyclopropane, (**2**) (1*R*,2*R*)-dideuterio-3,3-ditritiocyclopropane, (**3**) (1*R*,2*R*)-dideuteriooxirane, (**4**) (2*R*,3*R*)-dideuteriocyclopropanone, and (**5**) (2*R*,3*R*)-dideuterio-1,1-difluorocyclopropane (Figure 1). In each case, the deuteration pattern chosen had the same absolute stereochemistry as that for (1*S*,2*S*)-*trans*-1,2-dideuteriocyclopropane. The results are given in Table II. In each case the geometry was optimized with a 6-31G** basis set; and the force field, frequencies, and atomic polar and axial tensors were computed with the same 6-31G** basis set using the CADPAC programs[21] on an Ardent Titan

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Table II. Summary of the MFP and DCO Calculated C–H and C–D stretching VCD for Various Substituted Dideuteriocyclopropanes and Dideuteriocyclobutanes[a]

	MFP result					DCO orientation						
						ab initio			along bonds			
mode	ΔE	R^+	R^-	D^+	D^-	α	ΔE_d	R^+_d	ΔE_b	R^+	D^+	D^-
1 CH	−1.9	22.6	−39.3	4.0	33.8	18.9	3.0	3.9	1.7	6.8	2.8	35.0
CD	13.0	−11.1	10.6	5.0	28.1	17.7	2.5	−3.3	1.5	−4.4	2.4	30.6
2 CH	−4.0	29.1	−29.3	6.6	43.7	13.5	3.5	7.8	2.3	9.3	3.7	46.7
CD	13.3	−10.4	10.9	4.2	28.2	17.0	2.4	−3.1	1.5	−4.3	2.4	30.4
3 CH	−3.4	25.8	−32.9	5.8	70.0	8.1	4.8	10.8	3.7	9.6	3.0	72.8
CD	17.7	−14.6	16.9	7.7	59.3	15.6	4.9	−6.5	3.3	−6.3	2.6	64.4
4 CH	−5.4	0.6	−4.2	0.1	7.5	14.0	0.5	0.5	0.3	1.4	0.6	7.0
CD	8.7	−28.6	−0.5	9.6	3.4	50.0	0.5	−3.5	0.5	−1.8	1.0	12.0
5 CH	−4.0	1.2	−5.5	0.04	9.3	18.8	0.7	0.3	0.4	1.7	0.6	8.7
CD	11.3	1.8	0.5	1.2	4.1	15.4	0.3	−0.9	0.2	−0.7	0.4	5.0
6 CDe	−1.1	21.7	−22.1	12.6	62.2	15.7	4.8	10.3	2.6	8.5	3.6	71.6
CDa	9.3	35.2	−34.6	45.7	58.1	17.7	7.1	12.8	5.0	23.2	33.7	70.2
7 CHe	1.3	−84.2	84.7	60.3	83.2	12.8	9.4	−28.5	6.9	−43.5	46.5	97.0
CDe	−1.0	20.9	−22.6	11.2	65.6	16.5	4.9	10.0	2.7	8.7	3.6	73.1
CHa	−12.3	−45.5	44.9	13.2	93.2	11.7	5.5	−20.6	3.7	−16.4	5.0	101.0
CDa	9.5	33.7	−35.1	42.1	59.7	15.1	7.0	12.6	4.9	22.7	33.0	68.8
8 CH	−3.9	63.7	−56.6	35.7	96.6	12.9	7.9	29.8	5.2	34.3	21.6	110.7
CD	5.8	−26.2	17.4	27.9	70.6	15.6	6.3	−14.7	3.9	−18.8	16.1	82.4
9 CH	−4.0	2.7	14.4	0.47	15.7	20.0	1.2	1.2	0.7	4.1	2.5	13.7
CD	6.6	−0.8	−23.9	0.67	10.0	17.0	0.8	−0.8	0.4	−2.0	1.6	9.1

[a] Molecules defined in the text and Figure 1. Units and definitions as in Table I.

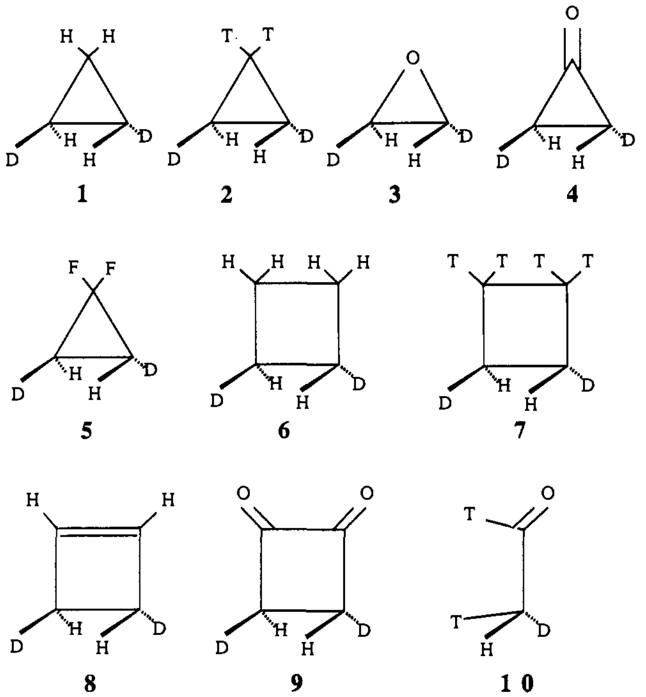

Figure 1. Schematic drawings of the molecules for which MFP and DCO VCD calculations are presented. (**1**) (1*S*,2*S*)-dideuteriocyclopropane, (**2**) (1*R*,2*R*)-dideuterio-3,3-ditritiocyclopropane, (**3**) (1*R*,2*R*)-dideuteriooxirane, (**4**) (2*R*,3*R*)-dideuteriocyclopropanone, (**5**) (2*R*,3*R*)-dideuterio-1,1-difluorocyclopropane, (**6** and **7**) two *trans*-d_2-cyclobutanes, (**8**) *trans*-d_2-cyclobutene, and (**9**) *trans*-d_2-cyclobutanedione, and (**10**) tritiated acetaldehyde, held in a rotameric form imitating **9**.

computer (P3 processor, 32 MB memory, 1.6 GB disk). D^k and R^k values were then computed using Stephens a priori MFP distributed origin gauge method as well as with the DCO model at two orientations as done above, and the results were compared.

For cyclopropane (**1**) a near conservative couplet is predicted for the C–D stretches and a less conservative one (negative bias) for the C–H stretches. Comparison of these results with those for the ditritiated cyclopropane (**2**) confirms that the inequality in the magnitudes of the C–H rotational strengths for **1** comes from mixing of the trans C–H stretches with those of the apex C–H groups in the normal modes derived from the force field. A more detailed comparison shows that the qualitative agreement in sign pattern and C–H vs C–D magnitude between DCO and MFP results is not matched quantitatively. Even for **2**, with no mode mixing problems, there is a difference of about a factor of 3 between the MFP and DCO R^k values.

This difference is even more accentuated if one considers the dipolar splitting. In all cases, the ab initio force field predicts the symmetric C–H stretch to be a few wavenumbers lower in energy than the antisymmetric C–H stretch. The opposite relationship holds for the C–D stretches, but the splitting is generally much larger. The dipolar coupling energy must have the same sign and be of comparable magnitude for both local modes due to symmetry considerations. Here it is calculated to be positive in the range 1–5 cm^{-1}, which would act to decrease the total C–H splitting and increase the C–D splitting. A combination of force field and dipole splitting thus could explain the difference in the ab initio splitting patterns computed for the C–H and C–D stretches.

As we move away from cyclopropane, a pure but strained hydrocarbon, to ethylene oxide (**3**), a significant loss of the conservative nature of the C–H VCD couplet is apparent. But for **3** there are no other C–H stretches, so the source here must not be mode mixing but, rather, center on interactions with or be caused by the heteroatom. Since, in terms of mass, O is not very different from CH_2 or CT_2, and since the two cyclopropanes give such similar results, it would seem reasonable to suspect that the difference in the VCD of ethylene oxide from that of cyclopropane arises from differences in their electronic structures. Due to the filled lone-pair orbitals primarily associated with the oxygen in ethylene oxide, this molecule should be more polarizable than is cyclopropane. Calculations at the DCO level involve only point dipoles so that they cannot reflect any potential contributions from polarizability.[2]

To carry this idea further, we calculated the same parameters for the cyclopropanone (**4**) and difluorocyclopropane (**5**). Here we see that Stephens's a priori MFP method computes virtually totally nonconservative VCD (i.e., single signed for all intents and purposes) for both the C–H and C–D stretches in **4** and highly nonconservative VCD for the C–H and single signed VCD for the C–D stretches in **5**. In the VCD of **4**, both modes are calculated to be negative indicating that the coupled oscillator contribution is totally unimportant for these modes, whereas in **5** the VCD of the C–H modes has a sign alternation while that of the C–D modes is just positive. Both of these molecules exhibit VCD patterns (at the level of MFP calculations) that are highly

Table III. Comparison of the MFP Computed VCD for the Dione (**9**) and *cis*-(*R*)-2-deuterio-1,2-ditritioacetaldehyde (**10**)[a]

	9			**10**		
mode	ν (cm^{-1})	R	D	ν (cm^{-1})	R	D
C—H asym	3266	14.7	15.7	3248	2.11	9.2
sym	3262	2.6	0.5			
C—D sym	2403	−0.8	0.7	2388	−7.28	7.1
asym	2396	−23.9	10.0			
C═O asym	2112	−13.9	354	2084	−6.03	328
sym	2093	1.4	570			

[a] Units and definitions as in Table I. Molecules defined in Figure 1.

deviant from the coupled oscillator model. In the case of the ketone, **4**, one might wish to attribute this deviation from the DCO contribution to increased polarizability due to the C═O function; but the same explanation would not work well for the difluoride, **5**. Thus the role of polarizability is uncertain. One could go through a number of possible explanations dealing with perturbations to electronic structure or mass distribution effects on the normal modes, but nothing in our results is decisive in this regard. We have attempted to carry out calculations on the hydrocarbon analogue of the ketone, methylenecyclopropane, $(CHD)_2C{=}CT_2$, for comparison; but the geometry did not converge to a minimum energy form when constrained to have all the carbons in a planar geometry.

Four-Membered Rings. A parallel set of calculations was made for two *trans*-d_2-cyclobutanes, $(CHD)_2(CH_2)_2$ (**6**) and $(CHD)_2(CT_2)_2$ (**7**), *trans*-d_2-cyclobutene, $(CHD)_2(CH)_2$ (**8**), *trans*-d_2-cyclobutanedione, $(CHD)_2(C{=}O)_2$ (**9**), and as a "best attempt" to represent "half" of the dione **9**, a tritiated acetaldehyde, (CHDT)(TC═O) (**10**), held in a rotameric form imitating **9** (Figure 1). The same overall pattern was evident, as seen in the three-membered ring series above, of gradual loss of agreement between the MFP results and the DCO predictions as the molecule was made more functionalized. As we have previously reported, using a simpler level of calculation,[13] and as recalculated at the MFP level,[10,26] the saturated hydrocarbon **6** yields near conservative C–H and C–D VCD both theoretically and experimentally. This pattern is evident in the C–D stretches of both the axial and equatorial conformers of **6**, but is more clear for the tetratritiated variant **7** since the C–H modes are also easily identifiable. However, closer inspection of the results for **7** reveals that the equatorial C–D modes and axial C–H modes are predicted to have the opposite sign pattern in the MFP and DCO level calculations due to oppositely signed energy splittings. It is this near-coupled-oscillator quantitative behavior of the VCD that led to the successes seen earlier[13] for simple theoretical models applied to understanding cyclobutane VCD.

If we increase the strain, the polarizability, and the level of delocalized electron density by considering now the unsaturated cyclobutene **8**, the MFP calculated VCD becomes less conservative but still yields qualitatively just the same patterns as seen with the DCO level calculation, again with the exception of the ΔE calculation for the C–H mode. Just as seen for the cyclopropane calculations, the magnitudes of the MFP calculated VCD are higher than for the DCO. In each of these examples, the energy splitting of the C–H and C–D modes have opposite signs with the ab initio force field but the same sign with just dipolar coupling. The magnitudes of the C–H and C–D splittings in **8** are more similar than those for the cyclopropane examples discussed above. In these cases, the dipole strengths could be used to assign the modes, should the experiment be done with adequate resolution, since $D^- \gg D^+$, as found for the cyclopropanes.

We have previously reported[9] that in its experimental spectrum the cyclobutanedione (**9**) has single-signed C–H (positive) and C–D (negative) VCD forming a highly nonconservative spectrum that can be well represented by calculations of R^k values at the MFP level. As is clear from Table II, or just from first principles, the DCO model cannot represent this experimental result at all. To better understand this dione **9** result, we have also calculated the VCD of an acetaldehyde (**10**) held in a conformation that mimics "half" of **9**. As summarized in Table III, our hypothetical "monoketone" (**10**) also has a positive C–H and negative C–D VCD calculated at the MFP level, just as seen experimentally and as calculated for the dione **9**. Additionally we calculate a negative VCD for the C═O transition, which was also computed for the dione **9**.[9] This calculative exercise strongly implies that the origin of the dione VCD is its local chirality and not dipole coupling. Furthermore, in this case the asymmetrical environment of the deuterated C must impose chirality on the carbonyl section of the molecule. This could be electrostatic through induced dipoles or mechanical through asymmetric coupling of the vibrational modes.

Discussion

Our calculations show that VCD due to the coupled oscillator mechanism is, in fact, apparent both quantitatively and qualitatively in the results of higher level calculations when applied to molecular transitions that are only very weakly coupled, which are ideal conditions for the DCO model. This observation may explain some of the current success seen in this model's applications to base deformation modes of nucleic acids.[11]

By contrast, our work also shows clearly that the DCO model misses much of the VCD intensity of more strongly coupled modes, even if the qualitative features in the experimental and MFP results are found in the DCO model calculations. When the molecule has features that lead to a loss of the qualitative aspects of the DCO type VCD, comparison with the MFP computations shows that the quantitative deficiencies of the DCO model are even greater. In particular, it seems that coupling of the local oscillators, represented by the C–H and C–D stretches in our calculations, to polarizable, heteroatom-containing modes leads to an increase in the overall R^k values as compared to the saturated hydrocarbon values. The pattern seen in this set of model calculations is one where the heteroatoms and electronically delocalized parts of the molecule lead to VCD originating from a different mechanism than that of the electrostatic coupling in the DCO model. The simple motions studied here couple to those sections of the molecule in a way that seems to dominate the dipolar coupling that would normally be seen in the saturated hydrocarbon parts.

Thus it seems that attempts to detail the VCD of multiple strongly coupled modes in small molecules using extensions of the coupled oscillator model used here are premature at present. While some qualitative agreement may be found with experiment, it does not seem that there can be much assurance of extension of these methods to molecules of unknown structure without an extensive data base being first built up to verify the trends suggested by the calculations done here. In other words, much of the effort in computational VCD has centered on the proving of theoretical models using molecules of known structure; however, the purpose or goal of VCD studies was originally to carry out structural determinations for molecules of unknown structure. Without a dominance of the phenomenon of VCD by the simple mechanism used to generate the DCO analysis, it will not be possible to generate reliable structural determinations using this simple model. Our results show that for a number of molecules with coupled oscillator-like spectra, that mechanism is still not dominant.

On the other hand, it is clear that a number of molecules have spectra that reflect the qualitative aspects of the DCO model. Our calculations have shown that if one were somehow to identify those molecules independently, the DCO model would give useful ste-

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reochemical information, particularly at the level of differentiating between a small number of quite different conformations or between two possible configurations. By contrast to this limited type of discrimination, use of the model to determine actual relative angular orientations between oscillators[7] is highly suspect due to the quantitative failings of the DCO results noted above. Most model calculations assume that the dipoles are located along the internuclear axes of the local oscillator. Our results show that at the ab initio level, the dipole orientations of C–H and C–D modes differ substantially from the bond axes due to coupling with other local modes. Even for the simple cyclopropane molecule with no degenerate oscillators to cause mode mixing, deviations from the bond axes as large as 10–20° (as indicated by α in Tables I and II) are calculated with the atomic polar tensors. Other types of modes, not centered on C–H motion, should be even more mixed.

A particular problem with the application of the DCO model as generally formulated is the need to determine the splitting mechanism (or its result) between the coupled modes. In the calculations described here, there was a consistent difference in the ab initio force field prediction (typically C–H and C–D stretches are predicted by the force field to couple with opposite signs) and the dipolar coupling result (both modes split the same way, as dictated by symmetry since no other oscillators are considered in the DCO model). Thus it would appear that any DCO-based method that is also dependent on the dipolar splitting to determine the relative ordering of the in- and out-of-phase coupled modes will have severe difficulty finding agreement with the MFP computed VCD. The extended coupled oscillator model of Freedman et al.[12] avoids this by using the results of a force field calculation to determine splittings. That solves the problem of *relative* agreement between the ΔE values for the two methods, DCO and MFP, but does not necessarily solve the problem of agreement with experiment.

It should be noted that the ab initio force field we calculated, or any other force field for that matter, may well have the relative ordering of these modes incorrectly determined. The only reliable method of determining such small splittings is to measure them experimentally using the differences in IR and Raman intensity patterns or the differences in D^k values for the two modes as has clearly been put forward earlier by Polavarapu[8] and Freedman et al.[6,12] For example, in these five cyclopropane cases the antisymmetric mode is expected to be 4–10 times stronger than the symmetric mode (with the sole exception of the C–D stretch in **4**). (The same holds true for the four-membered rings, but the ratio is smaller.) If one just does a simple coupled oscillator analysis of the dipole intensity, the same pattern is found, i.e., $D^- \gg D^+$ for both the C–H and C–D modes. Thus if the calculated frequency splittings are realistic, at least for the C–D stretches, it would be straightforward to use polarization ratios from Raman spectra to assign the modes properly. Generally resolution of such modes is a limiting factor in actually assigning them properly. This difficulty will make reliable application of the DCO model in all but the most ideal cases, i.e., with spectrally isolated oscillators, very limited.

While it certainly may be true that these ab initio force fields, especially at the SCF level, and the subsequent intensity determinations are still too approximate to use as a standard for judging all VCD analyses, they have proven quite reliable for a wide range of molecules when viewed in terms of overall predictability for the types of molecular modes studied experimentally. For several of the molecules specifically studied here, Stephens's a priori MFP calculations have also been shown to work well. The d_2-cyclopropane VCD is judged to be well fit by the MFP calculations,[12,22,24] and the same has been demonstrated for the d_2-epoxide.[23] The latter molecule's VCD has also been properly calculated with vibronic coupling theory.[25] The cyclobutane VCD was recalculated here with distributed origins but is still in good agreement with experiment and with simple fixed partial charge calculations[13] as well as with previous MFP calculations.[10,26] While those are examples where the DCO model at least qualitatively reflects the experiment, the cyclobutanedione results[9] did not, yet were also very well predicted with the MFP calculations. Thus Stephens's a priori MFP method has demonstrated a range of applicability for describing the VCD of these C_2 molecules made chiral by deuterium substitution.

If one surveys the performance of the MFP method by mode type, the C–H containing modes are often those for which one has the most difficulty in obtaining quantitative agreement with experiment. This may be the weakness of the calculations presented here. However, again for a number of these molecules, data is available and for the simple examples such as **1** and **6** as well as the more complex ones such as **2** and **9**, the MFP results are in excellent agreement with experiment. Thus we feel that the extrapolation made based on computational results alone to the series of more hypothetical molecules studied here is quite justified. The applicability of the DCO model, as would be extrapolated from this study, is thus suggested to lie in saturated hydrocarbon modes. This is consistent with those successes of the fixed partial charge[13] (which is essentially a dipole coupling model) and of the extended coupled oscillator[12] calculations that have been reported. Both these examples were based on careful analyses of the force field so that mode splittings were independent of the limitations of the electrostatic model.

Conclusion

Once justified, our results suggest that great care should be taken in applying the DCO model or its multiple oscillator variants to real molecular spectra. Lacking a characteristic conservative VCD spectrum, further application of the DCO model is clearly unwise due to the multiple, ill-understood sources for such an observation. Furthermore, dependence on a simplistic model for the splitting mechanism such as dipole coupling or simple force fields without experimental verification of the assignment can nullify a DCO-based interpretation. Even though our Table I results clearly do support the existence of the dipolar coupling effect, this interaction model is not very generalized nor is it typically dominant. Nucleic acid base modes are about the best real examples one can imagine. Even force field calculations can lead one astray due to the small splittings that often occur between weakly coupled local oscillators and the perturbations normally left out of the force field derivation, such as anharmonicity effects.

On the other hand, if the splitting and its sign pattern can be confirmed experimentally, and if the spectrum is approximately conservative, the results we present here suggest that the DCO method will give reasonable VCD sign patterns and, consequently, give stereochemical information that is of most interest to chemists. The immense saving in terms of computational effort more than counterbalances the experimental analysis needed to justify application of the appealingly simple DCO model for VCD spectral interpretation.

Acknowledgment. This work was supported by a grant from the National Science Foundation and in part by the donors of the Petroleum Research Fund administered by the American Chemical Society. We wish to thank Dr. Petr Malon for suggesting the acetaldehyde calculation and for carrying out some early computations, Dr. R. D. Amos for providing a version of CADPAC compatible with the Titan, and Professor Ron Elber for assistance in implementing it on the UIC facility.