n–π* Circular Dichroism of Planar Zig-zag Carbonyl Compounds

Alison Rodger *[,a] **and Mark G. Moloney** *[,b]
[a] Physical Chemistry Laboratory, South Parks Road, Oxford OX1 3QZ, UK
[b] Dyson Perrins Laboratory, South Parks Road, Oxford OX1 3QY, UK

A qualitative molecular orbital analysis has been developed to explain both the enhancement of magnitude and the red shift of the circular dichroism spectra of the first n–π* transition of carbonyl compounds which adopt a 'planar zig-zag' or 'W' conformation.

The circular dichroism (CD) of the n–π* transition of the carbonyl chromophore has been widely used in the determination of the absolute configuration and arrangement of substituents in molecules containing a carbonyl functional group.[1,2] The empirical 'octant rule' relationship† between the observed CD spectrum and the positions and polarizabilities of the various substituents is easy to apply and was generally found to be reliable. A molecular orbital (MO) rationale was provided for the octant rule by Moffitt *et al.*[3] Höhn and Weigang[4] later showed that this simple polarizability and geometry dependence requires the isotropic polarizability term from a perturbation theory expansion to be dominant. Rodger and Rodger[5] recently showed where the octant rule was inappropriate and how the n–π* CD of ketones with non-polar, polar or charged substituents in any position could be related to the geometry of the molecule. However, most CD spectra are measured in solution, rather than the gas phase, so the possibility exists that any theoretically determined geometry–CD correlation may be obscured by solvent effects.

In the context of CD spectroscopy, solvent effects can be divided into two categories, (*i*) those which provide an additional chiral perturbation of the chromophore, and (*ii*) those which provide a non-chiral perturbation which affects the energy, oscillator strength, conformation or identity of a substituent.

Category (*i*) was dealt with for adamantanones in ref. 5. It was shown that an achiral solvent will only provide a significant chiral perturbation if the molecule has a β-axial substituent, since such a substituent may force a very asymmetric solvent distribution in the region of the carbonyl chromophore. The neighbouring solvent molecules then become net perturbers and can affect the CD signal to the extent of changing its sign. The complicated solvent and temperature dependence of the CD of β-axial adamantanones[6,7] is thus accounted for. Category (*ii*) solvent effects are well known, and the blue shift of the n–π* transition with increasing polarity of the solvent is probably the archetypical solvent effect in spectroscopy.[8] The simplest way to account for such effects in comparing experiment and a semi-quantitative theory is to use experimental data obtained using a single solvent, and to study rigid framework stable molecules. Hydroxyfenchone[9] is an intriguing example where both categories of solvent effect are operative.

No attempt was made in earlier work[4,5] to address the question of the enhancement of the magnitude, and the red shift, of the CD signal which had been observed for planar zig-zag systems.[6,10–16] A perturbation theory analysis[4,5] begins with the assumption that the carbonyl n–π* transition (Fig. 1) occurs in a non-exchanging isolated chromophore; it cannot explain the zig-zag enhancement. If, however, the perturbation by which the rest of the molecule induces chirality in the planar carbonyl group involves transferring electron density to or from the carbonyl group then a perturbation theory approach requires modification; it would still be expected to be valid for the CD signs, but the magnitudes might vary from the predicted values.

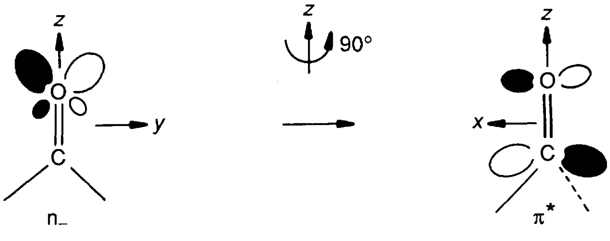


Fig. 1 A schematic illustration of the orbitals between which an electron is transferred in the n–π* transition of the carbonyl group. Symmetry requires that the n orbital is in fact the antisymmetric combination of the two oxygen lone pair orbitals. The π* orbital is in the plane perpendicular to the plane of the carbonyl group.

In this work, an investigation of changes in the electronic distribution of the ground and first excited state of the carbonyl group as a function of the geometry of the system is described. Such a change may be manifested experimentally both as a bathochromic or hypsochromic shift, and as a change in the magnitude of the intensity of the n–π* carbonyl transition. In particular, examination of the CD spectra of carbonyl-containing compounds has indicated that this effect is maximized for a planar zig-zag geometry of the alkyl substituent.[12] The principles developed in the explanation for this geometry dependence are expected to have wide applicability to any phenomenon which is dependent upon the electron distribution in one part of a molecule.

In this paper, the experimental evidence for enhanced magnitude and red-shifted n–π* transitions of zig-zag molecules is first discussed. A qualitative MO analysis of the effect of the zig-zag geometry on the energy of the orbital involved in the n–π* transition, and a reinterpretation of some earlier results then follow.

Experimental Results for n–π CD of 'Zig-zag' Ketones.*—There have been a number of reports of unexpected variations of the CD spectra of ketones. In general, a red shift and enhanced magnitude are observed for the various substitution patterns discussed below.

(a) *Unsubstituted ketones.* Kirk and Klyne[10] performed an extensive empirical analysis of n–π* data for ketones of the 'extended decalone' class (Fig. 2). They concluded that 'coplanar' zig-zag arrangements (Fig. 3) of the carbon–carbon

---

† The octant rule states that the contribution of a group, such as $-CH_3$, to the CD signal is proportional to its polarizability, and the factor $-xyz$, where (x,y,z) is the position of the substituent in the coordinate system of Fig. 1. The sign of the CD therefore follows an octant rule so that substituents in neighbouring octants make contributions of opposite sign. In addition, the magnitude decreases with distance of the substituent from the carbonyl.

Table 1 Wavelength of maximum absorbance, λ_{max}[17]; reduced CD strengths, R_{red} in dioxane;[17] and bond polarizabilities, α, for β-equatorial adamantanones for different substituents. $R_{red} = 1.08 \times 10^{40} R$, where $R = 0.696 \times 10^{-42} \int \theta(\lambda)/\lambda \, d\lambda$, θ = molecular ellipticity and λ = wavelength[2]

X	λ_{max} in dioxane[a]	R_{red}	α[b]	R_{red}/α
CH_3	290	2.23	1.3	1.7
Cl	295	13.36	6.51	2.1
Br	297	25.57	9.39	2.7
I	297	42.63	14.61	2.9

[a] See ref. 17. [b] A. I. Vogel, *A Textbook of Practical Organic Chemistry*, 3rd edn., Longmans, 1956; A. I. Vogel, *J. Chem. Soc.*, 1952, 514.

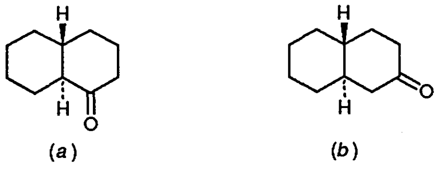


Fig. 2 The decalone class of compounds: (*a*) *trans*-1-decalone; (*b*) *trans*-2-decalone

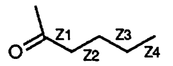


Fig. 3 Coplanar zig-zag arrangement of the carbon–carbon bonds in a ketone. Note that the C=O bond does not lie in the plane of the zig-zag.

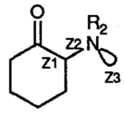


Fig. 4 2-Aminocyclohexanone, where Z1, Z2 and the nitrogen lone pair (Z3) form a zig-zag

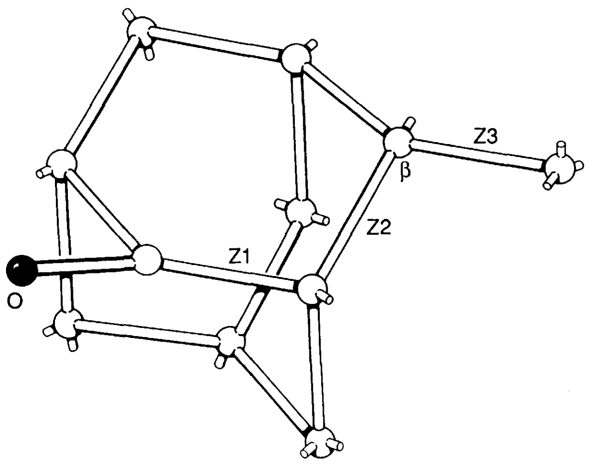


Fig. 5 β-Equatorial adamantanones. Z1, Z2 and Z3 form a zig-zag

bonds of substituents of these decalones have larger contributions to the decalone n–π* CD spectra than expected. If the bonds in a zig-zag from the carbonyl chromophore are denoted Z1 for the C–Cα bond, Z2 for the Cα–Cβ bond *etc.* then their results can be summarized by the rule: 'For hydrocarbon zig-zag ketones an enhanced magnitude and red shift of the n–π* CD is expected, and the effect of the even subchain (Z2, Z4, ...) is greater than the odd subchain (Z1, Z3, ...). The greater effect of the even subchain is due largely to the fact that the C–Cα bond is always part of a zig-zag, independent of the geometry of the rest of the molecule.

(b) *Amino-substituted ketones.* A similar effect has been observed in substituted ketone systems. Hudec *et al.*[13–16] considered the n–π* CD spectra of a range of aminocyclohexanones (Fig. 4). He demonstrated that, if the nitrogen is attached to C_α (so that Z2 is a C–N bond), and in addition the N-lone pair is antiperiplanar to Z1 (so that Z3 is the lone pair), then there is a red shift of the n–π* transition. Hudec[13] also noted that replacement of the nitrogen by oxygen slightly enhances this red shift, as does a Z4 nitrogen-lone pair.

(c) *Halo-substituted ketones.* Snatzke and Eckhard have synthesised a number of β-equatorial adamantanones[17] (Fig. 5), where Z3 is the C–X bond and Z4 is a lone pair. In Table 1 the CD strengths, bond polarizabilities and the ratios of these are given for X = methyl, chlorine, bromine, iodine. Previous work[5] showed that chlorine, bromine and iodine substituents induce CD *via* an octant rule bond polarization perturbation (*i.e.* no electron exchange), unless they lie on reflection planes of the carbonyl chromophore. As the geometry of β-axial methyl, chloro, bromo and iodo adamantanones are similar, their n–π* CD signals should therefore be proportional to the polarizability of the substituent, and the CD strength divided by substituent polarizability should be approximately constant (decreasing slightly as geometry variations are accounted for). These values are tabulated in Table 1 from which it is apparent that additional factor(s) must be operative in the β-equatorial adamantanones. This paper describes work which proposes the major additional factor to be the geometry of the side chain: a planar zig-zag array of the substituents leads to significantly enhanced n–π* transition intensities as observed in the spectrum. A red shift in the normal absorption and CD bands accompanies the enhanced magnitude.

Related results have been obtained from the UV spectroscopy of α-substituted carbonyl compounds (Fig. 6).[18a] For these molecules, the gauche conformation describes the zig-zag arrangement, so that variation of the C–X bond (Z2) will be responsible for the observed spectral changes. The red shift for substituted molecules increases in the series Et (279 nm), F (280 nm), MeO (283 nm), MeN = Cl (291 nm), Br (300 nm), I (306 nm), where the wavelengths are the maximum absorbances in hexane. (The situation is more complicated for the analogous series with a phenyl substituent.[18]) A similar red shift is observed for the β-equatorial adamantanones (*cf.* Table 1).

A clue to the direct influence of Z1 on the n–π* transition energy is provided by the compounds acetone, acetamide, acetic acid and urea. The CD spectra[19] induced by a chiral solvent indicate that both N_α and O_α cause a red shift, with that due to N_α being slightly larger.

Theory Applicable to n–π Carbonyl CD.*—The magnitude of the CD strength of a transition from the ground state, 0, to an excited state, 1, is given by the Rosenfeld equation [eqn. (1)] for

$$R = \mathrm{Im}\,[\boldsymbol{\mu}^{01}]\cdot[\boldsymbol{m}^{10}] \qquad (1)$$

the CD or rotational strength, R, which is analogous to the 'dipole strength'. Im denotes the imaginary part, $\boldsymbol{\mu}^{01}$ is the electric dipole transition moment (edtm) of the transition from state 0 to state 1 and $\boldsymbol{m}^{10}$ is the magnetic dipole transition moment (mdtm) of the reverse transition. For the carbonyl n–π* transition the ground state is one in which both of the non-bonding, or lone pair, orbitals on the oxygen are occupied by two electrons, and the excited state is one where only one of those electrons has been excited into the carbon–oxygen π* orbital. Since the isolated carbonyl chromophore has C_{2v} symmetry, the non-bonding orbitals are more correctly seen as the symmetry-adapted 'plus and minus' combinations, n_+ and n_-, illustrated in Fig. 7.[14] Thus the carbonyl n–π* transition is

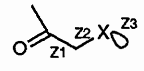


Fig. 6 *gauche* conformation of α-substituted carbonyl compounds

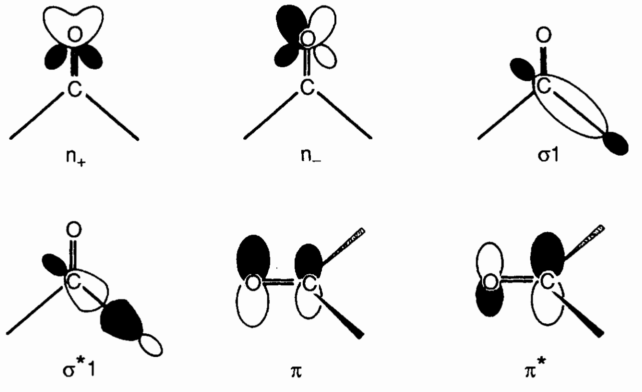


Fig. 7 Schematic illustration of the carbonyl valence orbitals. Shading indicates relative phase.

in fact the n_-–π^* transition.† This transition can be viewed as a rotation of the electron density from n_- into π^*, about the C–O bond (Fig. 1). Thus it has an intrinsic magnetic dipole transition moment. There is no intrinsic edtm as no linear motion of the n_- orbital results in net overlap with the π^* orbital. Thus for CD intensity to be observed, some electric character between the ground and excited states must be induced. Within an orbital picture this is equivalent to requiring perturbation of the n_- and π^* orbitals. In this work, N_- and Π^* are used to denote the perturbed orbitals corresponding to n_- and π^* respectively.

The enhanced CD observed for zig-zag geometries requires an increase in the mdtm and/or the edtm. A large value for the mdtm occurs when the shapes of the ground and excited states are similar, but rotated through 90° about the carbonyl bond. The edtm is more complicated since it arises in two ways. Edtm magnitude can be induced *via* a bond polarization mechanism,[4,5] which depends upon the polarizability of the substituents of the carbonyl and generally gives the octant rule behaviour. Alternatively, induction of an intrinsic edtm into the carbonyl group can occur by transfer of electron density from the substituents.

Kirk and Klyne[10] assumed that polarizability was the key to this unexpected behaviour of the zig-zag carbonyls, since in the zig-zag conformation the energy of the HOMO (highest occupied molecular orbital) is raised relative to other conformations, and therefore the HOMO contribution to the polarizability is increased. It is, however, unlikely that such a change in polarizability would be able to account for the significant CD magnitude changes which are observed. (The main reason for this is that the polarizability of saturated systems is dominated by transitions in the far UV, where many transitions are close in energy.) Thus the enhancement requires either an increase in mdtm or the creation of an intrinsic edtm. Of particular interest to this work are those interactions which are present only for a planar zig-zag arrangement of bonds.

Discussion

Geometry Dependent Perturbation of the n_- and π^* Orbitals.—Two well-known principles are the basis for the following discussion. (*i*) The extent to which any two orbitals interact is related to their overlap, and to the inverse of the difference in their orbital energies, $\Delta\varepsilon$. The main orbitals involved in the n_- and π^* perturbations are therefore valence orbitals of neighbouring bonds. The relevant orbitals are schematically illustrated in Fig. 7, and the variation of electron density about the nucleus for the different hybrid orbitals in Fig. 8. (*ii*) The interaction of any two orbitals results in one bonding orbital dominated by the lower energy component, and one antibonding orbital dominated by the higher energy component. (The antibonding combination is more antibonding than the bonding one is bonding.) The interaction of three orbitals results in one bonding, one antibonding and one intermediate combination.

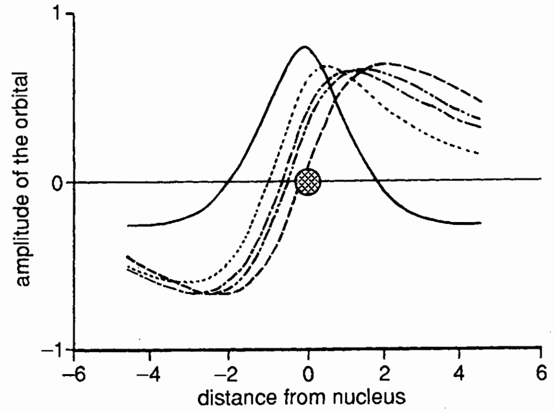


Fig. 8 The amplitudes along the bond axis and phases of hybrid orbitals from the mixing of s and p orbitals. Distance and amplitudes in arbitrary units. ●, Nucleus; ——, 2s; – – – –, 2p; · · · ·, 2sp; — · — · —, $2sp^2$; — — · · — —, $2sp^3$

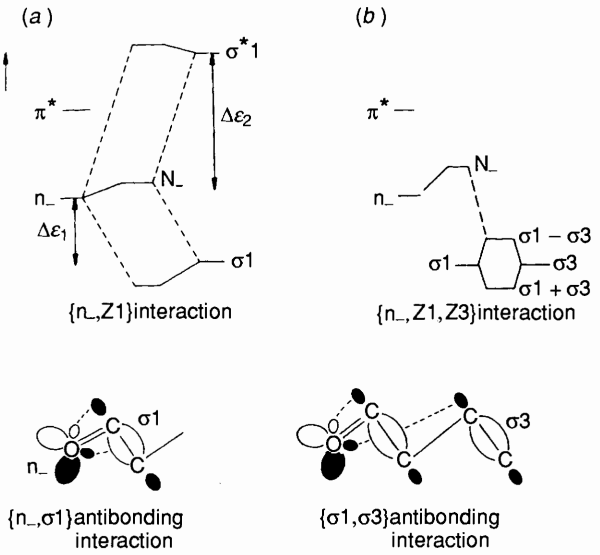


Fig. 9 (*a*) Interaction of the $\sigma 1$ and $\sigma^* 1$ orbitals of Z1 with n_-; (*b*) the effect of $\sigma 3$ on n_- *via* its coupling with $\sigma 1$

The perturbation of the n_-–π^* CD signal by a zig-zag hydrocarbon chain.—(*a*) *The perturbation of n_- by a zig-zag hydrocarbon chain.* The perturbation of n_- will be *via* the valence bonding, $\sigma 1$, and antibonding, $\sigma^* 1$, orbitals of the first link, Z1, due to the overlap constraint. When $\sigma 1$, $\sigma^* 1$ and n_- mix, the result is an (occupied) bonding orbital dominated by $\sigma 1$, an (unoccupied) antibonding orbital dominated by $\sigma^* 1$ and an (occupied) intermediate orbital, N_-, dominated by n_-. N_- is antibonding since $\Delta\varepsilon_1$ (the energy gap between n_- and $\sigma 1$) is smaller than $\Delta\varepsilon_2$ (the energy gap between n_- and $\sigma^* 1$)[20–22] (Fig. 9*a*). Z1 thus causes a red shift of the n–π^* transition since N_- is closer to π^* than is n_- of the isolated carbonyl group. Furthermore, N_- has more carbon character than n_-, leading

---

† Although n_- has the same symmetry as the $2p_y$ orbital it is bent, reflecting the contribution from $2p_x$ and 2s. The transition n_+–π^* is magnetic and electric dipole forbidden for symmetry reasons.

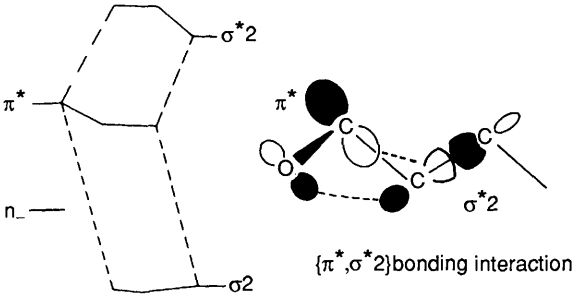


Fig. 10 Interaction of the $\sigma2$ and σ^*2 orbitals of Z2 with π^*

to an increased magnetic dipole transition moment, and hence an enhanced CD magnitude. However, since all ketones necessarily possess a Z1 bond, the experimental effect of a zig-zag chain for ketones is *via* changes in the $\{Z1, n_-\}$ interaction caused by successive links of that zig-zag chain.

When Z3 adopts a planar zig-zag arrangement with respect to Z1, the 'tails' of its sigma bonding, $\sigma3$, and antibonding, σ^*3, orbitals overlap with the orbitals of Z1. The Z1–Z3 interaction is dominated by the interaction between the approximately isoenergetic bonding orbitals $\sigma1$ and $\sigma3$, and antibonding orbitals σ^*1 and σ^*3 (Fig. 9*b*). The $\{\sigma1, \sigma3\}$ antibonding combination has large (approximately half) $\sigma1$ character and is closer in energy to n_- than $\sigma1$. Thus the interaction of n_- and $\sigma1$ is increased by having $\sigma3$ in the zig-zag arrangement, leading to a further red shift and magnitude enhancement. In addition, the Z3 perturbation is not coplanar with the carbonyl bond[†] (Fig. 5), and so a small intrinsic electric dipole transition moment is created. Subsequent odd-numbered bonds have smaller and smaller effects, but each serves to enhance the red shift and the transition moments. The even-numbered bonds have no effect on n_-.

(*b*) *The perturbation of* π^* *by a zig-zag hydrocarbon chain.* Because the hydrocarbon zig-zag is not coplanar with the carbonyl bond (Fig. 5) there is a net perturbation of π^* from its overlap with the sigma orbitals of Z2 (*cf. e.g.* refs. 15–17). Both valence bonding, $\sigma2$, and antibonding, σ^*2, orbitals interact directly with π^*. The energy difference $\Delta\varepsilon_3$ between π^* and $\sigma2$ is larger than the $\Delta\varepsilon_4$ between π^* and σ^*2 so the $\{\pi^*, \sigma^*2\}$ bonding interaction dominates the intermediate orbital, resulting in Π^* both being lower in energy than π^* and possessing more oxygen character (Fig. 10). In addition, since Z2 is not parallel to π^*, their interaction leads to an intrinsic edtm.

If Z4 continues the zig-zag, it perturbs π^* *via* its interaction with Z2. The bonding interaction of σ^*2 and σ^*4 results in an orbital with significant σ^*2 character which is closer in energy to π^* than σ^*2, so an increased perturbation of π^* by σ^*2 results.

(*c*) *The net effect of a hydrocarbon zig-zag chain on the n–*π^* *transition.* The effect of Z1 on an isolated carbonyl chromophore is to increase both the carbon character and energy of n_-, making its shape more like that of π^*, and reducing the energy required for a transition to π^*. Subsequent odd links in the zig-zag (Z3, Z5 etc.) enhance this effect. Similarly, a zig-zag Z2 increases the oxygen character of π^* and shifts it to lower energy, with Z4, Z6 *etc.* enhancing this effect. Thus each subsequent bond of a chain enhances both the red shift and the magnitude of the CD of the n–π^* transition, as has been observed experimentally.

The bonds Z2, Z3, *etc.* also create a small intrinsic electric dipole transition moment. If the zig-zag is viewed with the hydrocarbon chain in the plain of the paper and the carbonyl group projecting above it, then the $\{\sigma^*2, \pi^*\}$ bonding interaction distorts one lobe of Π^* towards Z2. This moves the lobe further to the right, and increases its size beneath the carbonyl bond as illustrated in Fig. 11*a*. In contrast, the interaction of the $\{\sigma1, \sigma3\}$ antibonding combination with n_- reduces the size of the underneath of the left hand lobe of n_- as illustrated in Fig. 11*b*.

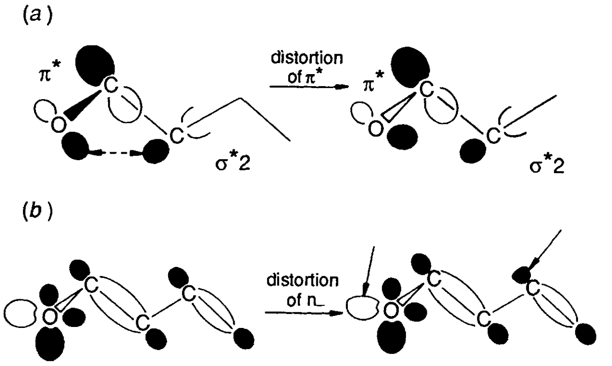


Fig. 11 The distortion of the π^*-(*a*) and n-(*b*) orbitals that lead to an intrinsic edtm on the carbonyl

Although the effect of Z1 on n_- in a hydrocarbon carbonyl is always present, the perturbation of π^* by Z2 is geometry dependent and a maximum for the zig-zag geometry.[20] Thus, Z2, being the closest net perturber to the carbonyl, dominates the perturbation of the n–π^* transition. This is in accord with the experiments of Kirk and Klyne.[10]

The effect of heteroatomic substituents in a zig-zag hydrocarbon chain.—The effect of heteroatomic atoms inserted into a hydrocarbon chain can be deduced in a manner analogous to that used above.

(*a*) *The effect on* n_- *of a heteroatom in a zig-zag*. Fig. 12 illustrates this discussion. If $\sigma3$ is an oxygen or fluorine lone pair, or a C–Cl, C–Br or C–I bond, then the $\{\sigma1, \sigma3\}$ antibonding combination lies between n_- and the $\{\sigma1, \sigma3\}$ antibonding combination of a hydrocarbon chain. This increases the perturbation of n_-. If, however, $\sigma3$ is a C–O, C–F or C–N bond then the $\{\sigma1, \sigma3\}$ antibonding combination lies below the hydrocarbon one and the opposite is true. If $\sigma3$ is a nitrogen, chlorine, bromine or iodine lone pair then it lies above n_- and so induces a blue shift and a magnitude decrease.

(*b*) *The effect on* π^* *of a heteroatom in a zig-zag.* An increased red-shifting perturbation of π^* requires σ^*2 to be at least part of an orbital which is closer in energy to π^* than a C–C antibonding orbital. Thus if Z2 or Z4 is C–Cl, C–N, C–O, C–Br or C–I then an increased red shift is expected. A C–F bond has little effect. Conversely, if Z2 or Z4 is a lone pair, and so there is no corresponding σ^*2 or σ^*4, then a blue shift relative to the unsubstituted hydrocarbon is expected.

(*c*) *The effect on the n–*π^* *transition of a heteroatom in a zig-zag.* The net effect on the spectroscopy of the replacement of a carbon of the zig-zag chain by a heteroatom is determined by the sum of the perturbations of the n_- and π^* orbitals discussed above.

C_α Replacement. Heteroatoms, X = O, N, are more electronegative than carbon and have a smaller effect on the isolated carbonyl n_- orbital than the parent hydrocarbon, as $\sigma1$ is now lower in energy. However, this is counteracted by an increased perturbation of π^*, as σ^*2 is also lower in energy. The net red shift is apparent from the dispersion-induced CD spectra of acetone, acetic acid, acetamide and urea (see above).[19]

C_β Replacement. If, for example, nitrogen replaces C_β then Z2 = C–N bond. σ^*2 is now closer to π^* than for an unsubstituted molecule, resulting in an increased red shift and

---

[*] The carbonyl group is not in the same plane as the hydrocarbon part of the zig-zag, since the carbonyl carbon is sp^2 hybridized. For an idealized geometry the angle the C=O bond makes with the plane of the hydrocarbon zig-zag is *ca.* 45°.

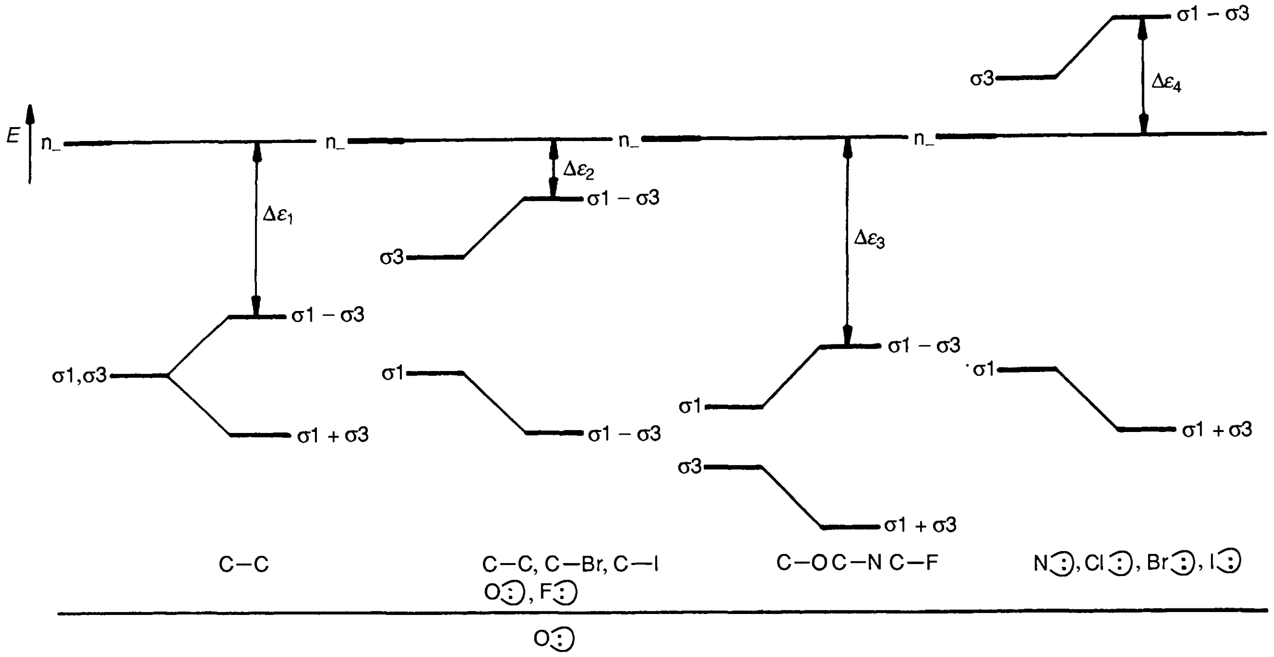


Fig. 12 The effects of different energy σ3 orbitals on n_

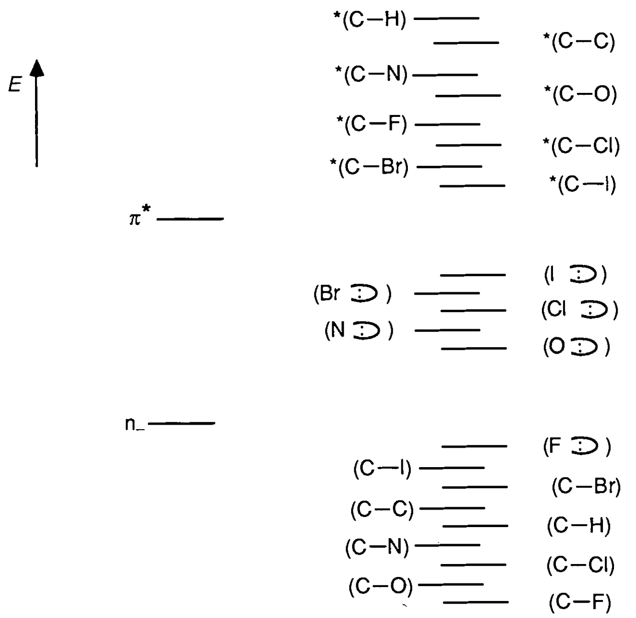
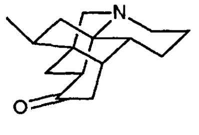
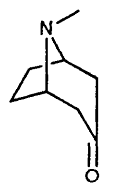


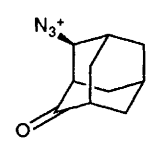
Fig. 13 Schematic diagram illustrating the energy order of sigma bonding and antibonding and lone-pair orbitals relative to n_ and π*. Ordering determined from ref. 26 and minimal basis-set calculations performed using MOPAC. Calculations on particular systems are to be found in the literature.[5,6,10,14,15]

magnitude enhancement. The shift of the normal n–π* absorption (in hexane) from 279 nm for $EtCH_2COMe$ to 291 nm for $(Me)_2NCH_2COMe$ illustrates this effect.[22] A similar situation is expected for O_β, and the maximum UV absorbance is at 283 nm for $MeOCH_2COMe$. As Fig. 13 indicates, σ*2(C–O) should perturb, and hence lower, π* more than σ*2(C–N) does. The larger red shift of the amine results from similar Z2 perturbations from O_β and N_β but larger Z3 perturbations from the O_β lone pairs which oppose the red shift. For the heteroatoms chlorine, bromine and iodine there will therefore be increasing red shifts (291 nm, 300 nm and a shoulder at 306 nm respectively[22]) and magnitude enhancement, as σ*2 comes closer to π* along that sequence, and the opposing effect of the Z3 lone pair decreases along the same series. For an F_β, the small energy gap between σ3 (F lone pair) and n_, makes the Z3 perturbation comparatively large, and results in almost no change from the unsubstituted molecule (280 nm[22]).

C_γ Replacement. For the case where Z3 is a carbon–nitrogen bond, the {σ1, σ3} antibonding combination is lower in energy than in the hydrocarbon case so the perturbation of n_ is less than in the unsubstituted case (Figs. 12 and 13). This reduction is reinforced when Z4 is a nitrogen lone pair. Thus a γ-nitrogen results in decrease of the CD magnitude and a blue shift relative to the corresponding hydrocarbon. Owing to the first three links of the chain, however, a net red shift and enhancement will be observed relative to a corresponding non-zig-zag molecule. Although Hudec[13] suggested that a γ-nitrogen should enhance the red shift, the three examples (**1**–**3**) used to support this hypothesis are inconclusive. Ketone **1** has its n–π* maximum at 284 nm in ethanol. This is actually *blue* shifted compared with other molecules which have three or four members of a hydrocarbon zig-zag,[14,21] although it is red shifted compared with a non-zig-zag molecule. The spectrum of ketone **2** was obtained under conditions in which the amine would be protonated and, therefore, Z4 is an N–H bond rather than a lone pair. His third example follows from considering a lone pair to be localized on the first nitrogen of the N_3 of β-equatorial azido-adamantanone (**3**). Comparison of the azide absorption and CD bands[8,16] with those of other equatorially substituted adamantanones does not provide definitive evidence of either a red or a blue shift.


1


2


3

The effect of Cl_γ, Br_γ and I_γ is in contrast to that of nitrogen, since for these substituents σ3 is closer to n_ than in the hydrocarbon analogue, and an increased red shift and magnitude

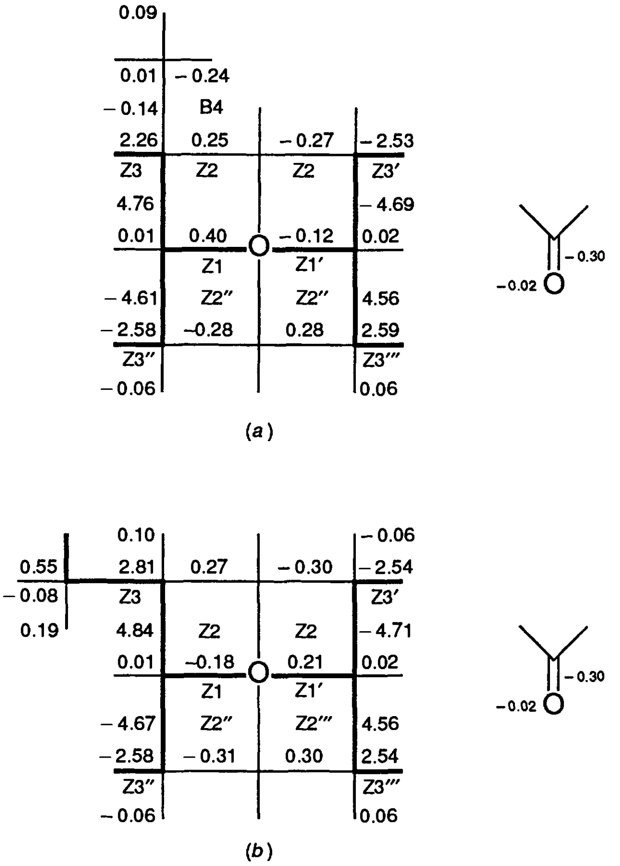


Fig. 14 Calculated contributions made by each bond to the total CD for (*a*) β-axial and (*b*) β-equatorial methyladamantanone from ref. 6. Molecules are viewed projected into the plane perpendicular to the C=O bond. Zig-zags are indicated by a thick line.

enhancement is expected. The work of Snatzke and Eckhard[17] discussed above serves to illustrate this point.

Qualitative Orbital Analysis Approach Compared with Accurate Calculations.

The above discussion has implications for the interpretation of the theoretical calculations of the n–π* CD spectra of ketones which have been reported by Lightner, Bouman and Hansen.[6,11,12]

Bouman and Lightner[11] performed semiempirical calculations on simple ketones held at fixed geometries and provided the first computational support for the zig-zag enhancement of CD which had been noted earlier by Kirk and Klyne.[10]† By considering methyl ethyl, ethyl propyl and propyl butyl ketones they were also able to show that carbon–carbon bonds further along the zig-zag had less effect on the CD spectrum than those close to the carbonyl. Their calculations on 1-aminopentan-3-one (where the net effect is due to the Z3 C–N bond and the nitrogen lone pair, whose position was varied by rotating it about Z3) also demonstrated that the largest induced edtm was obtained when the nitrogen lone pair continued the zig-zag.

Subsequent to this work Hansen and Bouman[6,12] used the Random Phase Approximation Method to calculate the CD spectra of β-substituted adamantanones. By localizing the occupied molecular orbitals of the ground and excited states, determination of the contribution made to the n–π* transition by each bond or lone pair of a molecule could be made. Representative results for β-axial and β-equatorial adamantanones are given in Fig. 14. The numbers on the carbonyl group reflect the CD resulting from the induced intrinsic edtm on the carbonyl. For the axial isomer the effect of the four Z3 bonds cancel, giving a very small value of −0.02 on the n_- orbital. The four Z2 bonds similarly have no net effect on π*. However, the bond labelled B4 is in a zig-zag type arrangement with Z2″, thus reinforcing the perturbation of Z2″ relative to the other Z2 bonds. A net CD contribution of −0.3 is attributed to the π* orbital. For the equatorial isomer, the Z3 carbon–carbon bond induces a net positive n_- CD contribution of 0.22. The π* value of 0.52 is due to the reinforcement of the Z2 interaction by its Z4 C–H bond.

The bond entries for the rest of the molecule are the sum of the polarizability-induced CD contribution and the zig-zag enhancement contribution. As discussed above, for a hydrocarbon a zig-zag increases the magnitude of the CD. However, this does not imply that each bond in a zig-zag should have an increased CD contribution. For example, the {σ1, σ3} antibonding orbital, which increases the perturbation of n_-, has 50% σ1 character and 50% σ3 character, thus this zig-zag CD enhancement is divided between the two bonds Z1 and Z3. A further complication in the adamantanones is the cancellation of contributions from symmetrically disposed parts of the molecule. The similarity of the numbers on the right hand side (Fig. 14) of the two isomers (except for Z1) indicates that no electron exchange interactions with the substituents are relevant for those bonds in accord with the distance from the substituents. The small difference in the Z2″ entries for the two isomers is related to the zig-zag type interaction noted above for the axial Z2″ with B4. The resulting enhancement of the contribution of Z2″ to the CD is reflected in the negative entry on B4. The zig-zag arrangement of Z2 and Z4 (a C–H bond) in the equatorial isomer results both in the slightly larger value on Z2 and a large entry (given its distance from the carbonyl) of 0.55 on Z4. Similarly, the Z3 bonds in both isomers have a large contribution to the CD due to the Z3 enhancement of the Z1 perturbation of n_-. The entries on Z1 and Z1″ for each isomer are the sum of a number of cancelling contributions.

Conclusions

This work has provided qualitative insight into how the successive bonds on a coplanar zig-zag of bonds in a carbonyl molecule perturb the n–π* transition. The perturbation of the transition occurs *via* the interactions of the n_- orbital with the orbitals of the C–C_α bond, Z1, and π* with the orbitals of C_α–C_β, Z2. Subsequent odd and even bonds influence the transition by their perturbations of the orbitals of Z1 and Z2 respectively. The zig-zag geometry is a prerequisite for the overlap of *e.g.* Z1 and Z3 orbitals, which enable the observed relative enhancement of magnitude and red shift of carbonyl n–π* CD in zig-zag molecules relative to non-zig-zag molecules to be rationalized.

The perturbation of n_- is dominated by its antibonding overlap with σ1, the valence bonding orbital of Z1. This raises n_-, thus shifting the transition to the red, and gives it more carbon character, thus increasing the CD magnitude. Z3, Z5 *etc.* perturb n_- by first perturbing σ1. If σ3 (the sigma bonding orbital of Z3) is lower in energy than n_-, then its effect is to increase the perturbation of n_-. A heteroatom in Z3 will have a larger effect than a carbon atom if, and only if, its σ3 lies between n_- and σC–C.

The largest detectable perturbation of the n–π* transition is usually *via* the σ*2–π* bonding overlap. (The n_-–σ1 interaction is generally approximately constant across a series of compounds.) This interaction decreases the π* energy, thus

---

† The δΔε values of Kirk and Klyne[10] cannot be compared directly with the bond contributions of ref. 5 since Kirk and Klyne experimentally determine the net effect of an additional bond irrespective of whether it contributes directly or *via* perturbing another bond.

redshifting the transition, and increases its oxygen character, thus increasing the magnitude of the CD. Z4, Z6 *etc.* perturb π^* by first perturbing σ^*2. The σ^*4–σ^*2 bonding interaction increases the perturbation of π^*. Heteroatoms may increase the perturbation if their σ^*4 lies between σ^*2 and π^*. Lone pair Z4's have no effect, so, relative to a hydrocarbon Z4, they reduce the perturbation of π^*.

Electronic interactions, which are geometry dependent (and are maximized for a planar zig-zag or W geometry) have been widely described as the 'stereoelectronic effect'.[23–25] A similar theoretical treatment would be expected to provide a more detailed understanding of other situations where geometry dependent electronic factors are important, *e.g.* the well-known 'W-effect' observed for hydrogen chemical shifts in NMR spectroscopy, and the 'anomeric effect' observed for carbohydrates.

Acknowledgements

A. R. now appreciates Aa. E. Hansen's challenge to consider the enhanced CD magnitudes of zig-zag chains and is grateful for financial support from Unilever. M. G. M. gratefully acknowledges financial support by Glaxo Group Research (UK). Very helpful comments from one of the referees are acknowledged with thanks.

References

1 L. Velluz, M. Legrande and M. Grosjean, *Optical Circular Dichroism*, Verlag-Chemie GMBH, Academic Press Inc., New York, 1965.

2 C. Djerassi, *Optical Rotary Dispersion*, McGraw-Hill, New York, 1960. There is an extremely large body of literature on carbonyl n–π^* CD. The references given below relate specifically to the zig-zag enhancement of the CD. References in them lead on to the main body of carbonyl CD literature.

3 W. Moffit, R. B. Woodward, A. Moscowitz, W. Klyne and C. Djerassi, *J. Am. Chem. Soc.*, 1961, **83**, 4013.

4 E. G. Höhn and O. E. Weigang, *J. Chem. Phys.*, 1968, **48**, 1127.

5 A. Rodger and P. M. Rodger, *J. Am. Chem. Soc.*, 1988, **110**, 2361.

6 D. A. Lightner, T. D. Bouman, W. M. D. Wijekoon and Aa. E. Hansen, *J. Am. Chem. Soc.*, 1986, **108**, 4484.

7 G. Snatzke, B. Ehrig and H. Klein, *Tetrahedron*, 1969, **25**, 5601.

8 H. McConnell, *J. Chem. Phys.*, 1952, **20**, 700.

9 R. C. Cookson, *Proc. R. Soc. London, A*, 1967, **297**, 27.

10 D. N. Kirk and W. Klyne, *J. Chem. Soc., Perkin Trans. 1*, 1974, 1076.

11 T. D. Bouman and D. A. Lightner, *J. Am. Chem. Soc.*, 1976, **98**, 3145.

12 Aa. E. Hansen and T. D. Bouman, *Mol. Phys.*, 1979, **37**, 1713.

13 J. Hudec, *J. Chem. Soc., Chem. Commun.*, 1970, 829.

14 M. T. Hughes and J. Hudec, *J. Chem. Soc., Chem. Commun.*, 1971, 805.

15 G. P. Powell and J. Hudec, *J. Chem. Soc., Chem. Commun.*, 1971, 806.

16 A. H. Beckett, A. Q. Khokhar, G. P. Powell and J. Hudec, *J. Chem. Soc., Chem. Commun.*, 1971, 326.

17 G. Snatzke and G. Eckhardt, *Tetrahedron*, 1968, **24**, 4543.

18 (*a*) S. A. Guerrero, J. R. T. Barros, B. Wladislaw, R. Rittner and P. R. Olivato, *J. Chem. Soc., Perkin Trans. 2*, 1983, 1053; (*b*) P. R. Olivato, S. A. Guerrero, Y. Hase and R. Rittner, *J. Chem. Soc., Perkin Trans. 2*, 1990, 465.

19 P. E. Schipper and A. Rodger, *Spectrochim. Acta Part A*, 1988, **44**, 575.

20 R. Hoffman, *Acc. Chem. Res.*, 1971, **4**, 1, and references therein.

21 C. C. Levin, R. Hoffmann, W. J. Hehre and J. Hudec, *J. Chem. Soc., Perkin Trans. 1*, 1973, 210.

22 N. L. Allinger, J. C. Tai and M. A. Miller, *J. Am. Chem. Soc.*, 1966, **88**, 4495.

23 G. Descotes, M. Lissac, J. Delmau and J. Duplan, *C.R. Hebd. Séances Acad. Sci., Ser. C*, 1968, **267**, 1240.

24 P. Deslongchamps, *Stereoelectronic Effects in Organic Chemistry*, Pergamon Press, Oxford, 1983.

25 A. J. Kirby, *The Anomeric Effect and Related Stereoelectronic Effects at Oxygen*, Springer-Verlag, Berlin, 1983.

26 L. Salem and W. L. Jorgensen, *The Organic Chemists Book of Orbitals*, Academic Press, New York, 1973.

Paper 0/04874G
Received 25*th October* 1990
Accepted 30*th January* 1991