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MAGNETIC CIRCULAR DICHROISM OF CYCLIC π-ELECTRON SYSTEMS—20†[1]

AMINO DERIVATIVES OF INDOLE, AZAINDOLES, AND PURINES

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Abstract—The simple perimeter model combined with PMO theory is used to rationalize and predict trends in MCD spectra of substituted azaindoles and similar heterocycles bearing a single electron-donating mesomeric substituent, such as serotonin and adenine.

Magnetic circular dichroism of cyclic π-electron systems derived from a (4N+2)-electron perimeter by perturbations such as cross-linking, introduction of heteroatoms and substituents etc., can be understood in simple terms.[2-4] According to the perimeter model,[5] such π-electron systems are characterized by four low-energy electronic excitations, which we shall refer to as L_1, L_2, B_1, and B_2 in the order of increasing energy. The MCD activity of an electronic transition is reflected in the sign and magnitude of the corresponding peak in the MCD spectrum, and is usually measured quantitatively by defining the B term of the transition, $B = -33.53^{-1}\int d\tilde{\nu}[\theta]_M/\tilde{\nu}$, where $\tilde{\nu}$ is wavenumber and $[\theta]_M$ is the magnetically induced molar ellipticity per unit magnetic field (deg. $L.m^{-1}$ mol^{-1} G^{-1}). Note that a positive peak in the MCD spectrum corresponds to a negative B term.

The application of a modified perimeter model to MCD spectroscopy described in Refs. 2–4 and summarized in qualitative terms in the preceding paper in this series[1] permits the B terms of the L and B transitions of molecules derivable from a (4N+2)-electron perimeter to be expressed in terms of two types of contributions. One of these, referred to as the μ^--contribution, is essentially structure-independent and provides small positive values for the B terms of the two L bands, a larger positive value for the B terms of the B_1 band, and a larger negative value for the B term of the B_2 band. In those molecules derived from (4N+2)-electron perimeters in which the separation of the top two occupied orbitals (ΔHOMO) is equal to the separation of the bottom two empty orbitals (ΔLUMO), referred to as soft MCD chromophores, the μ^--contributions to the MCD of the L and B bands are the only ones present. The μ^--contributions to one or both of the L bands may actually vanish in certain instances, predictable from molecular structure, and a sub-classification of soft chromophores has been proposed.[4] If ΔHOMO ≠ ΔLUMO, a second type of contribution to the B terms of the four bands exists. These are referred to as μ^+-contributions and are potentially much larger. If ΔHOMO > ΔLUMO, the signs of the μ^+-contributions to the L_1, L_2, B_1, and B_2 bands are +, −, +, and −, respectively (positive-hard chromophore). If ΔHOMO < ΔLUMO, the signs are −, +, −, and +, respectively (negative-hard chromophore). Since perturbation such as substitution can easily remove the equality of ΔHOMO and ΔLUMO in a soft chromophore, MCD signs of the L bands of such chromophores are susceptible to dramatic changes upon minor structural changes (the MCD signs of the B_1 and B_2 transitions are harder to affect since the intrinsic μ^--contributions are larger). Frequently, substituent effects on the sign of the ΔHOMO-ΔLUMO difference can be predicted using first-order perturbation theory.[4] The positions of a soft chromophore are classified with respect to substituent effects on ΔLUMO as +E-dominant (D) if $c^2_1 > c^2_{-2}$, +E-subdominant (S) if $c^2_1 < c^2_{-2}$, and +E-neutral (N) if $c^2_1 \cong c^2_{-2}$. Similarly, they are classified with respect to effects on ΔHOMO as −E-dominant if $c_1^2 > c_2^2$, -E-subdominant if $c_1^2 < c_2^2$ and −E-neutral if $c_1^2 \cong c_2^2$. Here, the four frontier orbitals are labelled 2, 1, −1, −2 in the order of the increasing energy. Both ΔHOMO and ΔLUMO are equally susceptible to an inductive effect, but ΔLUMO responds primarily to electron-withdrawing +E mesomeric effects while ΔHOMO responds primarily to electron-donating −E mesomeric effects. These substituent effects follow readily from PMO theory. A not-too-strong +E substituent increases (decreases) ΔLUMO if it is in a +E-dominant (+E-subdominant) position. A not-too-strong −E substituent increases (decreases) ΔHOMO if it is in a −E dominant (−E-subdominant) position. On the other hand, a very strong +E (−E) substituent will induce ΔHOMO < ΔLUMO (ΔHOMO > ΔLUMO) regardless of the position of substitution, since it may induce a switching of the order of the two orbitals involved. A complete qualitative specification of the nature of a position to mesomeric effects is thus given by stating both abbreviations, e.g. D,S, and we have chosen[4] to arrange them in the order +E, −E. A +I substituent increases (decreases) ΔLUMO if it acts on a position which is +E-dominant (+E-subdominant) and simultaneously decreases (increases) ΔHOMO if the position is −E-dominant (−E-subdominant). A −I substituent has just the reverse effect. The overall effect of an I substituent on ΔHOMO-ΔLUMO can then be obtained by summing the effects on ΔHOMO and ΔLUMO. If $c_2^2 - c_1^2 + c^2_{-2} - c^2_{-1} = \Delta(\Delta HOMO\text{-}\Delta LUMO)/(-\Delta\alpha)$ is positive, the position is of an I-subdominant type (+I effect causes ΔHOMO > ΔLUMO, −I effect causes the opposite). If

†Dedicated to Professor Michael J. S. Dewar on the occasion of his 60th birthday.

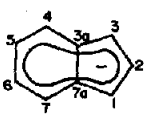
$\Delta(\Delta HOMO\text{-}\Delta LUMO)/(-\Delta\alpha)$ is negative, the position is of an I-dominant type (+I effect causes $\Delta HOMO < \Delta LUMO$, −I effect causes the opposite). In odd-soft chromophores and even-soft chromophores, which are derived from uncharged (4N + 2)-electron [4N + 2]annulene perimeters, alternant pairing of the MO's limits the choices to certain combinations of D, S, and N, Thus, in an odd-soft chromophore only DD, SS, and NN positions occur, and a position which is, say, I-dominant, must also be + E-dominant and − E-dominant. The same applies to subdominant or neutral positions, so that one can briefly refer to the three types of positions as D, S, and N. In an even-soft chromophore, only DS, SD, and NN positions occur to a reasonable approximation. All positions are I-neutral, i.e. inductive substitution has little or no effect on ΔHOMO-ΔLUMO and as a result, only the three above stated distinct labels are needed. In single-soft chromophores, which are derived from a charged (4N + 2)-electron perimeter, all four principal possibilities, DD, DS, SD and SS can occur for the effects of mesomeric substituents, and the label describing the inductive effect must be specified independently. A summary of substituent effects on ΔHOMO-ΔLUMO is given in Table 1.

Substituent effects in π-electron systems derived from uncharged perimeters have already been investigated in detail (Ref. 6 and the immediately following papers). In the preceding paper in this series,[1] we have reported an investigation of a system derived from the [9] annulenide perimeter, namely the indenide anion $C_9H_7^-$, which is a nearly single-soft chromophore, and of a series of its isoelectronic heterocyclic analogs such as indole and N-methylpurines. We found that the simple theory provides a satisfactory qualitative understanding of the MCD spectra from first principles in this instance, too.

In the present paper, we use the same model to analyze the effects of −E substituents on the MCD spectra of heterocycles isoelectronic with the indenide anion. The biological importance of the compounds of this type has already spurred several MCD investigations. Results for adenine,[7] serotonin,[8,9] several aminoindoles and methoxyindoles,[10] and N-methyl derivatives of adenine[11] and 8-azaadenine[12] have been published. We now report the MCD spectra of 7-aminoindole, 5−, 6−, and 7-aminoindazoles, and 2-aminobenzimidazole, and provide an interpretative discussion of the general MCD behavior of this class of compounds. It must be kept in mind that the perimeter model involves numerous simplifications, discussed in Refs. 2–4, and can only be expected to produce qualitative or at best semiquantitative results: its strength lies in producing simple physical insight, general rules, and prediction or rationalization of trends. We also provide a comparison of our MCD spectra with the numerical results of a more complex but still rather naïve approach, namely π-electron PPP calculations.

RESULTS AND DISCUSSION

The MCD spectrum of the indenide anion **1** has been discussed and found to agree well with expectations based on the simple model.[1] Because of the approximate equality of ΔHOMO and ΔLUMO in this nearly single-soft chromophore, perturbations can easily induce an inequality in either direction and thus induce either sequence of signs for the μ^+-contributions to the B terms of the L and B bands.



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The S,D characterization of the positions of **1**, taken from Ref. 1, is given in Table 2. Positions 3a, 4, and 5 resemble the positions 8a (SS), 1 (DD), and 2 (SS) of the odd-soft naphthalene chromophore, respectively, while positions 1 and 2 are reminiscent of the positions 1 (SD)

Table 1. Substituent effects on (ΔHOMO-ΔLUMO)

Type of Substituent	Type of Position[a] Dominant (D)	Neutral (N)	Subdominant (S)[b]
+E	$c_{-1}^2 > c_{-2}^2$	$c_{-1}^2 \simeq c_{-2}^2$	$c_{-1}^2 < c_{-2}^2$
Action	Increases ΔLUMO	Little	Decreases ΔLUMO
-E	$c_1^2 > c_2^2$	$c_1^2 \simeq c_2^2$	$c_1^2 < c_2^2$
Action	Increases ΔHOMO	Little	Decreases ΔLUMO
+I	$(c_2^2 - c_1^2 + c_{-2}^2 - c_{-1}^2) < 0$[b]	$(c_2^2 - c_1^2 + c_{-2}^2 - c_{-1}^2) \simeq 0$	$(c_2^2 - c_1^2 + c_{-2}^2 - c_1^2) > 0$
Action	Decreases (ΔHOMO-ΔLUMO)	Little	Increases (ΔHOMO-ΔLUMO)
-I	$(c_2^2 - c_1^2 + c_{-2}^2 - c_1^2) < 0$	$(c_2^2 - c_1^2 + c_{-2}^2 - c_1^2) \simeq 0$	$(c_2^2 - c_1^2 + c_{-2}^2 - c_1^2) > 0$
Action	Increases (ΔHOMO-ΔLUMO)	Little	Decreases (ΔHOMO-ΔLUMO)

[a] A lower case letter indicates a weak S or D character and thus a weaker response to substituent effects. The quantity $c_2^2 - c_1^2 + c_{-2}^2 - c_{-1}^2$ is equivalent to $\Delta(\Delta HOMO\text{-}\Delta LUMO)/(-\Delta\alpha)$ to first-order in perturbation theory.

[b] The action stated applies to weak substituent effects. Very strong E substituents will act in all positions as if they were of type D.

Table 2. Characterization of positions in the indenide anion 1 with respect to mesomeric substituent effects

	Position				
	1=3	2	3a=7a	4=7	5=6
$c_{-1}^2 - c_{-2}^2$ (+E)	-0.043	0.118	-0.071	0.268	-0.214
$c_1^2 - c_2^2$ (-E)	0.253	-0.317	-0.145	0.104	-0.052
Position type	ND	dS	sS	Dd	Ss

and 2 (dS) of the even-soft azulene, respectively. The greater complexity of the single-soft chromophore, **1**, is thus apparent.

In order to predict the MCD signs of −E substituted indoles and azaindoles by first-order perturbation considerations, we first introduce a suitable model for a −E substituent into various positions. From the above we expect that substitution in the −E-dominant positions 1=3 and 4=7 will produce a positive value for ΔHOMO-ΔLUMO, more so in the former than in the latter, while substitution in the −E-subdominant positions 2 and 5=6 will produce a negative value for ΔHOMO-ΔLUMO, more so in position 2 than in 5=6. As always in the case of substitution in a subdominant position, this will only hold if the −E substituent is not too strong. If its electron-donating strength increases too much, the energy of orbital 2 will increase above that of orbital 1 and further increase in the substituent strength will lead first to a reduction of the induced negative value of ΔHOMO-ΔLUMO until it reaches zero, and then to its gradual increase towards positive values. Thus, a sufficiently strong −E substituent will produce a positive value for ΔHOMO-ΔLUMO not only in a dominant position, but also in a subdominant one. This theoretically anticipated sequence of events as a function of substituent strength has been experimentally demonstrated on the case on an odd-soft chromophore (naphthalene)[13] and an even-soft chromophore (pyridine)[14] but so far not on a single-soft chromophore.

Standard PPP calculations were performed for the four isomeric amino derivatives of **1**. The values of $\Delta(\Delta HOMO\text{-}\Delta LUMO)/(-\Delta\alpha)$ obtained from the relevant MO coefficients are collected in Table 3 and have the same signs in a given position in all four amines. The signs are the same as in **1** itself and even the magnitudes are rather similar in all cases, permitting a joint discussion. Table 3 also shows the calculated ΔHOMO-ΔLUMO values whose signs and relative magnitudes agree with those anticipated for a −E substituent which is not excessively strong and does not change orbital ordering.

The next step is the replacement of a $-CH^-$-unit by a heteroatom which donates two π electrons, such as -NH-. Its inductive effect on ΔHOMO-ΔLUMO can be predicted by first-order perturbation theory, as described above, using the quantities $\Delta(\Delta HOMO\text{-}\Delta LUMO)/(-\Delta\alpha)$ listed in Table 3, and remembering that a positive value corresponds to an I-subdominant position, a negative value to an I-dominant position, and that for an electronegative heteroatom ($\Delta\alpha < 0$) this translates into a more positive (less negative) ΔHOMO-ΔLUMO for the former (S) and a less positive (more negative) ΔHOMO-ΔLUMO for the latter (D). Finally, any additional aza heteroatoms which may be present need to be introduced. These provide weaker perturbations in the same sense as the NH replacement and will be treated similarly. A more accurate description would be obtained by first introducing the NH heteroatom explicitly, recalculating the MO coefficients, and using perturbation theory only for the description of the effect of the additional aza heteroatoms, but this approach would generate a much larger number of separate special cases.

We are now ready to use Table 3 to discuss trends in the MCD spectra of −E substituted azaindoles, azabenzofurans, and similar heterocycles, focusing on the L_1 and L_2 transitions, easily identifiable in most cases. At the same time, we shall compare the results with the available experimental data, both the new spectra presented in Figs. 1–5 and the spectra previously published.[7-12] In many of our spectra a third transition can

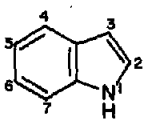
Table 3. Characterization of positions in the aminoindenide anions with respect to the inductive effect of heteroatom replacement

	Position							
Δ(ΔHOMO - ΔLUMO)/(-Δα):	1	2	3	4	5	6	7	ΔHOMO - ΔLUMO (eV)
1	-0.22	0.22	-0.22	-0.30	0.26	0.26	-0.30	0.1
1-NH_2 - 1	-	0.26	-0.08	-0.25	0.21	0.17	-0.29	0.5
2-NH_2 - 1	-0.17	-	-0.17	-0.30	0.23	0.23	-0.30	-0.6
4-NH_2 - 1	-0.14	0.43	-0.21	-	0.22	0.16	-0.34	0.3
5-NH_2 - 1	-0.28	0.16	-0.15	-0.30	-	0,27	-0.37	-0.1
Type of response to I effect	D	S	D	D	S	S	D	

be recognized. It has been labeled as no. 3 and is assigned as the B_1 transition. Its B term is always positive, similarly as in the indenide anion 1 itself. In 1, this has been assigned as due to the μ^--contribution (B_1-B_2 mixing). Even in the presently discussed heterocycles, where ΔHOMO-ΔLUMO may be quite negative, the μ^+-contribution to the B term of the B_1 band is apparently not strong enough to change this sign to negative.

The observed signs of the B terms of the L_1 and L_2 transitions are collected in Chart 1. We have also performed PPP calculations of the B terms for all possible amino derivatives of indole, indazole, benzimidazole, and benzotriazole, and verified all the trends discussed qualitatively in the following. Of course, the qualitative method of interpretation is more powerful than a numerical calculation in that it is immediately equally applicable to other heterocycles derived from 1 and to other −E-substituents. Table 3 suggests that several distinct possibilities should exist:

(i) The amino group is in one of the −E-dominant positions of 1, 1 = 3 or 4 = 7, so that ΔHOMO-ΔLUMO is relatively large and positive. It will require considerable further perturbation by the heteroatoms to reverse the sign of ΔHOMO-ΔLUMO and to make the signs of the μ^+-contributions anything but +, − for the B terms of transitions L_1 and L_2, respectively.



1-NH-1

Additional Substituents and Aza Heteroatoms	L_1	L_2	Ref.
2-NH_2-3N-	−	+	−
4-NH_2-	+	−	10
4-NH_2-3-N-	+	−	10
4-NH_2-3, 5, 7-N-	+	−	7
4-NH_2-3, 5, 7-N-1-CH_3-	+	−	11
5-NH_2-	−	+	10
5-NH_2-2-N-	+	+	—
5-CH_3O-	−	+	10
5-HO-3-$NH_2CH_2CH_2$-	−	+	8
6-NH_2-2-N-	−	+	—
6-CH_3O-	−	+	10
7-NH_2-	−	+	—
7-NH_2-2-N-	+	−	—
7-NH_2-3, 4, 6-N-1-CH_3-	+	−	11
7-NH_2-2, 3, 4, 6-N-1-CH_3	+	−	12
7-CH_3O-	−	+	10

Chart 1. Experimental signs of B terms in substituted indoles (1-NH-1) and azaindoles

If an electronegative heteroatom is placed into one of the I-subdominant positions, 2, 5, or 6, the already large positive ΔHOMO-ΔLUMO will be only increased, and the +, − sign sequence for the B terms reaffirmed. Only the positioning of one or more heteroatoms into the I-dominant positions, 1, 3, 4, and particularly 7, has the potential for reducing ΔHOMO-ΔLUMO and thus the positive B term of transition L_1 and the negative B term of transition L_2, or perhaps even reversing their signs. All experimental data available for 4-NH_2 or 7-NH_2 derivatives are for compounds of this type, in which the effect of the −E-substituent is opposed to that of the 1-NH heteroatom, making absolute predictions difficult. Even numerical calculations are likely to have trouble unless they can really exactly evaluate the two opposed tendencies. Experimentally (Chart 1), one indeed finds evidence for a closely balanced situation. On the one hand, the 1-NH heteroatom does not prevail over a 4-NH_2 substituent (4-aminoindole, +−), even when assisted by a (much weaker) 3-aza heteroatom (4-aminobenzimidazole, +−) or in the presence of 3, 5, 7-triaza "substitution" (adenine and 9-methyladenine, +−). On the other hand, it prevails over a 7-NH_2 substituent (7-aminoindole, −+), but just barely: for instance, when the 7-NH_2 group is aided by a 2-aza heteroatom, it wins (7-aminoindazole, +−). This role of a 2-aza heteroatom is also reflected in the much smaller magnitude of the B terms of the L transitions of 7-methyl-8-azaadenine[12] relative to 7-methyladenine[11]. Since the 1-NH heteroatom prevails over a 7-NH_2 substituent, it is only reasonable that it should also dominate over the weaker 7-CH_3O substituent as is observed (7-methoxyindole −+). The fact that it is easier for the 1-NH heteroatom of overwhelm a 7-NH_2 substituent than a 4-NH_2 substituent, or otherwise expressed, that a 4-NH_2 substituent puts up more resistance to a 1-NH heteroatom than to a 3-NH heteroatom, is also confirmed by the smaller magnitude of the B terms of the L transitions of 7-methyladenine relative to 9-methyl-

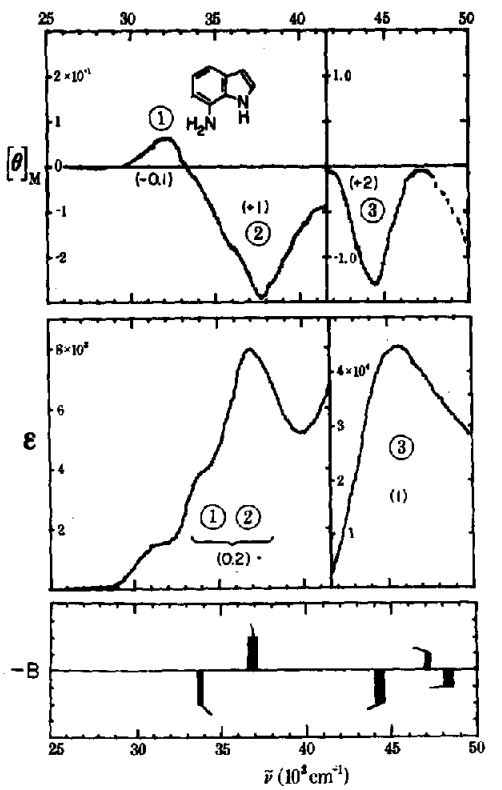


Fig. 1. 7-aminoindole: Top, MCD (B terms given in units of $10^{-3}\beta_e D^2/cm^{-1}$); center, absorption (oscillator strengths given); bottom, PPP calculation. Calculated −B values are indicated by the length of the bars (short, below 1; medium, 1 to 5; long, greater than 5; in units of $10^{-3}\beta_e D^2/cm^{-1}$). Calculated oscillator strengths are indicated by their three grades of thickness (less than 0.1, 0.1 to 1, greater than 1), and calculated polarizations by directions of the flags at the end with respect to the formula as drawn.

adenine[11] and is in good agreement with the Δ(ΔHOMO-ΔLUMO)/(−Δα) values in Table 3: that for position 1 of 4-NH_2-**1** is only two thirds of that for position 3. However, it would have been impossible to predict from the qualitative argument that the sign switch will occur just between these two cases. Even the PPP method has difficulty estimating correctly the balance of the two factors and predicts incorrectly the signs of the B terms for 7-aminoindole (Fig. 1) and 7-methoxyindole.[10] Conversely, a fit of these MCD spectra is likely to provide a sensitive way for calibration of heteroatom parameters in the PPP method.

The enhancement of the magnitude of the B terms of the L transitions of 9-methyladenine[11] upon protonation contrasted with a reduction in their magnitude in the case of 7-methyladenine[11] suggests that the protonation occurs on the aza nitrogen ortho to the NH_2 group in the former and the aza nitrogen para to the NH_2 group in the latter, (i.e. in positions 5 and 4, respectively, using our numbering).

The discussion has concentrated exclusively on the μ^+-contributions so far. However, in cases of near equality of ΔHOMO and ΔLUMO it is probably important to consider the μ^--contributions as well. The general formulas of Ref. 3 show that these operate primarily by L_1-B_1 and L_2-B_2 magnetic mixing and provide a small positive contribution to the B terms of the L_2 transitions, and an even smaller one to that of the L_1 transition. These are presumably observed in the spectra of **1** itself[1]. This helps to account for the generally observed tendency for the lowest B term to be smaller in absolute magnitude if the sign sequence is −,+ and larger if the sign sequence is +,−.

(ii) The amino group is in the strongly −E-subdominant position 2 of **1**, so that ΔHOMO-ΔLUMO is relatively large and negative. It will require considerable further perturbation by the additional heteroatoms to reverse the sign of ΔHOMO-ΔLUMO and to make the signs of the μ^+-contributions anything but −,+ for transitions L_1 and L_2, respectively. It is in the nature of a subdominant position such as 2 that this can be achieved in principle in two ways. The additional electronegative heteroatoms could counteract the effect of the 2-NH_2 group by being placed in the −E-subdominant positions 5 and 6. Alternatively, they could be placed into one of the −E-dominant positions, 1, 3, 4, or 7, where they would reinforce the action of the 2-NH_2 group to the point where the orbitals 1 and 2 cross and beyond, where further increase in −E-substituent strength leads to positive values for ΔHOMO-ΔLUMO. The one experimental example available, 2-aminobenzimidazole, is of this latter type. The B term of its L_1 transition is still negative (Fig. 2), but is very small and it is probable that a further slight push in the same direction, say protonation on N3 or aza replacement in position 4 would already change its sign into positive.

(iii) The amino group is in the very weakly −E-subdominant positions of **1**, 5 = 6, and the difference ΔHOMO-ΔLUMO is negative but very small. The sign of ΔHOMO-ΔLUMO thus has a very good chance to be dominated by the heteroatoms with only a small bias towards negative values provided by the −E-substituent. Placing a heteroatom into an I-dominant position of 5-NH_2-**1**, i.e. 7, 4, 1, or 3 in the order of decreasing efficiency, will serve to make ΔHOMO-ΔLUMO more negative and will reinforce the expected −,+ sign pattern for B terms. Indeed, 5-aminoindole,[10] 5-methoxyindole,[10] 5-hydroxytryptamine,[8,9] and 6-methoxyindole[10]

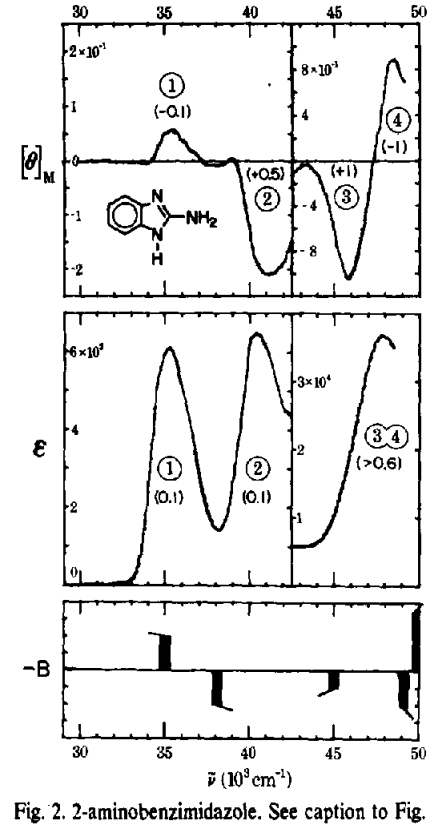


Fig. 2. 2-aminobenzimidazole. See caption to Fig. 1.

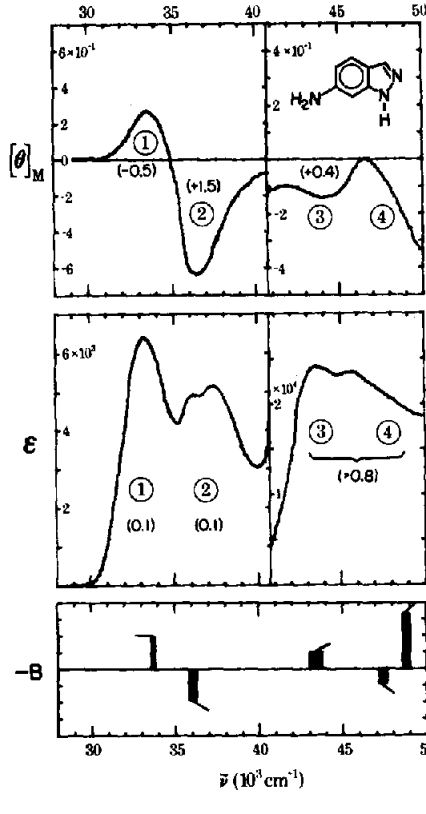


Fig. 3. 6-aminoindazole. See caption to Fig. 1.

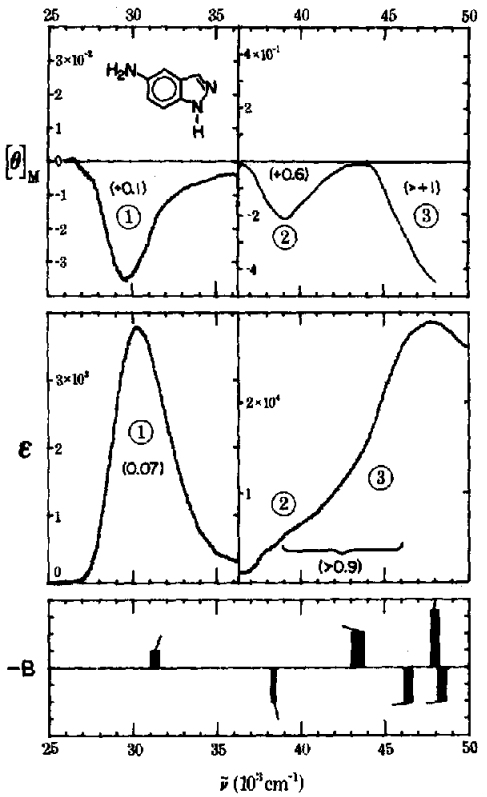


Fig. 4. 5-aminoindazole. See caption to Fig. 1.

all show the −,+ sign sequence typical of indole itself. The magnitudes of their B terms appear to be significantly affected by the considerable differences in the L_1-L_2 energy separation within this group of compounds.

A more interesting situation develops if one or two heteroatoms are placed in the I-subdominant positions of 5-NH_2-1, i.e. 6 and 2 in the order of decreasing efficiency. If their effect is strong enough, the sign sequence should revert to +,−. The only experimental comparison possible at present is with 6-aminoindazole (−,+, Fig. 3) and 5-aminoindazole (+,+, Fig. 4). The former can be viewed as a 3-NH-2-N derivative of 5-NH_2-1 the latter as its 1-NH-2-N derivative. The weak tendency of 5-NH_2-1 towards a negative ΔHOMO-ΔLUMO difference is countered in each case by the aza heteroatom in position 2 and supported by the NH heteroatom, strongly if it is in position 1 and only half as strongly if it is in position 3 (Table 3). We would expect the combined forces of the 5-NH_2 substituent and the NH heteroatom to overwhelm the effect of the 2 aza heteroatom in both compounds and produce ΔHOMO < ΔLUMO. Such is also the outcome of PPP calculations, but of the two experimental spectra, only that of 6-aminoindazole exhibits the −,+ sign sequence, expected from the simple argument and from the PPP calculation, while that of 5-aminoindazole shows a distinctly positive first B term, albeit very weak, and a stronger positive second B term.

We believe that the disagreement is only apparent and can be understood as follows: the sign of ΔHOMO-ΔLUMO is negative as expected, and the signs of the μ^+-contributions to B terms are −,+ for L_1 and L_2 transitions, respectively, as expected, but the former is unusually weak and does not prevail over the positive intrinsic μ^--contribution. We believe that the unusual reduction of the magnitude of the μ^+-contribution to the B term of the L_1 transition results from the large separation of the energies of the L_1 and L_2 states in 5-aminoindazole. This is about 10,000 cm^{-1} (Fig. 4), to be compared with 3000 cm^{-1} in the 6-aminoindazole isomer (Fig. 3) and similar small values in the other indole analogs considered here. The large energy split is reproduced fairly well by PPP calculations, which also suggest that this is a general property of 5-aminoazaindoles. To understand why an increase in the L_1-L_2 separation relative to the L_1-B_1 separation must reduce the μ^+-contribution to the lowest B term regardless of its sign, one needs to notice the detailed form of the general formulas on p. 6814 of Ref. 3. The μ^+-contribution to the B term of L_1 consists of a part due to L_1-L_2 mixing by the magnetic field and an opposed part due to L_1-B_1 mixing. The magnitude of each part is inversely propotional to the energy separation of the states which are being mixed. Normally, the L_1-L_2 separation is so much smaller than the L_1-B_1 separation that the effect of magnetic L_1-B_1 mixing represents only an insignificant reduction in the size of the μ^+-contribution to the B term of L_1. However, as the L_1-L_2 and L_1-B_1 separations become more nearly equal, the cancellation becomes more nearly complete and the magnitude of the μ^+-contribution to the B term of L_1 decreases. If the two energy separations were equal, it would actually vanish. In 5-aminoindazole, they are about 10,000 cm^{-1} and 18,000 cm^{-1}, respectively, so that the difference of their inverses is 0.04×10^{-3}, and this can be compared with 6-aminoindazole, where they are about 3000 cm^{-1} and 11,000 cm^{-1}, respectively, so that the difference of the inverses is an order of magnitude larger, 0.24×10^{-3}. It should be noted that there is no analogous cancellation effect weakening the μ^+-contribution to the B term of L_2, since in this case the effects of the two magnetic mixing contributions provided for the B term (L_2-L_1, L_2-B_2) add up rather than cancel.[3] Such a cancellation occurs instead in the μ^--contribution to the B term of L_2, but so far has never been observed to be of practical importance. The μ^+-contribution to the B term of the L_2 transition of 5-aminoindazole thus corresponds in the normal fashion to the anticipated negative value of ΔHOMO-ΔLUMO and is positive, as is the intrinsic μ^--contribution, and the L_2 transition appears normal in the MCD spectrum.

The reason why the PPP calculation fails to reproduce the +,+ sign sequence for the B terms of 5-aminoindazole is probably the same as the reason for which it generally does rather poorly for the B terms of the B_1 and B_2 transitions, namely, it appears to underestimate the μ^--contributions, which dominate these B terms. The μ^--contributions are largely due to next-nearest-neighbor interactions, absent in the usual version of the PPP method. They have been built into the calculations reported here, but in an admittedly rather *ad hoc* fashion which apparently still underestimates them. With or without the non-neighbor terms, which are unimportant for the μ^+-contributions, our PPP calculations numerically support the qualitative argument given above for the much reduced magnitude of the μ^+-contributions to the B term of the L_1 transition in 5-aminoindazole relative to 6-aminoindazole, and for the roughly equal size of the μ^+-contributions to the B terms of the L_2 transitions in the two amines.

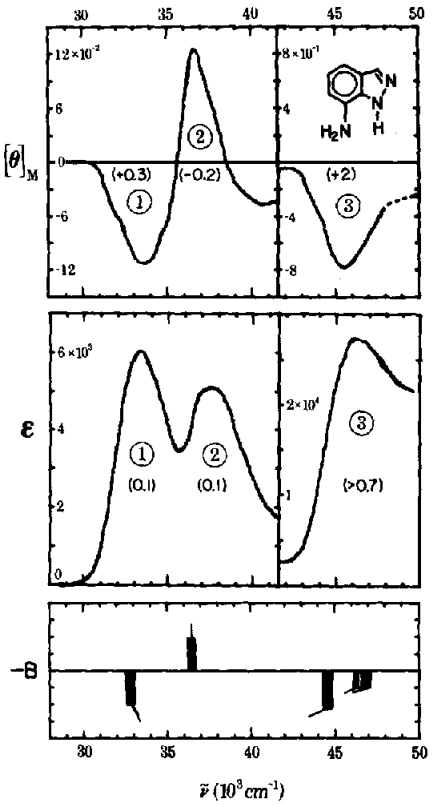


Fig. 5. 7-aminoindazole. See caption to Fig. 1.

CONCLUSION

The simple model of Refs. 2–4 permits prediction and/or rationalization of trends in the long-wavelength region of the MCD spectra of azaindoles and related heterocycles carrying −E-substituents, but leaves room for quantitative improvements. Although explicit consideration of the involvement of a larger number of excited states, including $\sigma\pi^*$ states, $n\pi^*$ states etc., may be necessary if quantitative agreement is to be achieved, there is no indication that it is needed for a qualitative interpretation of the MCD effect of the first two $\pi\pi^*$ transitions.

EXPERIMENTAL AND CALCULATIONS

2-Aminobenzimidazole and 5-, 6-, and 7-aminoindazoles were commercial samples. 7-aminoindole was prepared by Raney nickel catalyzed reduction of the corresponding nitro compound.[15] The samples were purified by gradient sublimation and the spectra measured in spectral grade acetonitrile. The techniques of measurement and B term evaluations were those of Ref. 6.

Calculations were performed as in Ref. 6 using the higher value of 10.15 eV for A_N+. The matrix elements of the magnetic dipole moment operator between atomic orbitals on next-nearest-neighbors were set to −0.15 times the values for nearest neighbours.[16]

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REFERENCES

[1]Presented in part at the Northwest Regional ACS Meeting, Reno, Nevada, June 1976. For Part 19 see M. A. Souto, S. L. Wallace, and J. Michl, *Tetrahedron* **36**, 1521 (1980).
[2]J. Michl, *J. Am. Chem. Soc.* **100**, 6801 (1978).
[3]J. Michl, *Ibid.* **100**, 6812 (1978).
[4]J. Michl, *Ibid.* **100**, 6819 (1978).
[5]J. R. Platt, *J. Chem. Phys.* **17**, 484 (1949).
[6]A. Castellan and J. Michl, *J. Am. Chem. Soc.* **100**, 6824 (1978).
[7]W. Voelter, R. Records, E. Bunnenberg, and C. Djerassi, *Ibid.* **90**, 6163 (1968).
[8]F. M. Sprinkel, D. D. Shillady, and R. W. Strickland, *Ibid.* **97**, 6653 (1975).
[9]G. Barth, R. E. Linder, E. Bunnenberg, and C. Djerassi, *Helv. Chim. Acta* **55**, 2168 (1972).
[10]D. W. Miles and H. Eyring, *Proc. Nat. Acad. Sci., U.S.A.* **70**, 3754 (1973).
[11]R. E. Linder, H. Weiler-Feilchenfeld, G. Barth, E. Bunnenberg, and C. Djerassi, *Theor. Chim. Acta* **36**, 135 (1974).
[12]H. Weiler-Feilchenfeld, R. E. Linder, G. Barth, E. Bunnenberg, and C. Djerassi, *Ibid.* **46**, 79 (1977).
[13]M. R. Whipple, M. Vašák, and J. Michl, *J. Am. Chem. Soc.* **100**, 6844 (1978).
[14]S. L. Wallace, A. Castellan, D. Muller, and J. Michl, *Ibid.* **100**, 6828 (1978).
[15]S. P. Hiremath and S. Siddappa, *J. Karnatak Univ.* **9–10**, 13–15 (1964–65).
[16]N. H. Jørgensen, P. B. Pedersen, E. W. Thulstrup, and J. Michl, *Int. J. Quant. Chem.* **12**, 419 (1978).