Thermodynamics of Hydrogen Bond Formation from Temperature Dependent C.D. Spectroscopy

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A linear regression analysis of c.d. data is used to obtain enthalpies and entropies of formation of cyclic hydrogen-bonded dimers of all-*trans*-retinal and hexadienal Schiff bases.

We have shown recently¹ that the Schiff base (1) obtained from all-*trans*-retinal aggregates in aprotic solvents to form what we assume is a hydrogen-bonded cyclic dimer (A_2) . Starting with a chiral amine, the formation of the homochiral dimer is shown by c.d. spectroscopy; with the polyene chains extending from the same face of the ring, interaction of the chromophores results in two excitations separated by twice the interaction energy and each associated with high rotatory strength of opposite sign. Analysis of u.v. and c.d. intensities led us to propose a structural model in which the two chromophores make an acute angle of about 60° with each other.

The aggregation is strongly temperature and concentration dependent. In Figure 1, the symbols denote the combined $\Delta \epsilon$

values of the two Cotton effects as they develop with decreasing temperatures for three different concentrations of (1). As judged from the rotatory strengths, aggregation in a 1.23×10^{-4} M solution (Figure 1b) is negligible at room temperature and essentially complete at 153 K, while in a solution which is 4-fold more concentrated (Figure 1a), aggregation is clearly discernible at room temperature and approaches its final value around 190 K. At a lower concentration (Figure 1c), aggregate formation is shifted towards lower temperatures.

We report now that using a linear regression analysis we have been able to extract from the c.d. data standard

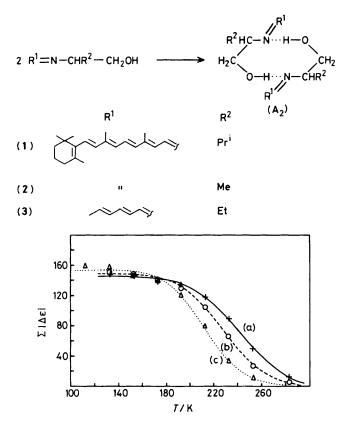


Figure 1. Temperature dependent c.d. spectroscopy of (1) for three different concentrations. $\Sigma |\Delta\epsilon|$ is $|\Delta\epsilon_+| + |\Delta\epsilon_-|$, the sum of the exciton-split dimer absorptions. Symbols represent experimental values, while the curves give the best theoretical fits. For numerical results, see Table 1. Concentrations: (a), 4.9×10^{-4} M; (b), 1.23×10^{-4} M; (c), 2.22×10^{-5} M. Solvent: Rigisolve (2,2-dimethylbutane– n-pentane 8:3).

thermodynamic parameters which describe the monomerdimer equilibrium, independent of concentration over the whole temperature range.

$$2A \rightleftharpoons \widehat{AA} \rightleftharpoons \widehat{AA}$$
(1)

We assume an overall equilibrium (1) (A_2 denoting the closed cyclic dimer) with equilibrium constant $K = a_{A_2}/a_A^2$ and standard free energy change $\Delta H^\circ - T\Delta S^\circ = -RT \ln K$. We assume, furthermore, that there exist in solution just two chiral species, *viz.* the monomer A and the dimer A_2 with individual (temperature independent) rotatory strengths R_A and R_{A_2} . Starting with an arbitrary choice of ΔH° and ΔS° , values for R_A and R_{A_2} are computed which best fit the observed temperature dependence of the rotatory strength. Then, the computation is repeated with different values for ΔH° and ΔS° until maximum correlation with experiment is achieved. The curves drawn in Figure 1 indicate the excellent fit between calculated and experimental data; the numerical results are collected in Table 1, together with results for two other Schiff bases, (2) and (3).

A measure of the quality of the regression analyses is provided by the correlation coefficients r which for none of the calculations is less than 0.999. All regressions show a high degree of convergence, r decreasing rapidly upon moving away from the optimum ΔH° and ΔS° values. It is gratifying to note that for the computations the variable R_A proves to be redundant. In all cases, R_A comes out close to zero indicating that the rotatory strengths measured are due to the dimer only.

Temperature dependent c.d. spectroscopy has been proposed before² and used, among others, by us³ to extract conformer populations and thermodynamic data for equilibria involving chiral species. That method, however, is limited in that it is only amenable to processes with temperature independent standard free enthalpies, ΔG° .

All three dimers analysed by our method have negative standard enthalpies and entropies of formation as might have been expected.⁴ It appears that the length of the polyene chains extended from the ring has no influence on the stabilities of the dimers, the one from the hexatrienylidene Schiff base forming as easily as the ones from all-*trans*retinylidene Schiff bases. On the other hand, the larger ΔH° -value for (2) as compared to (1) and (3) may reflect the size of the small methyl group as compared to an isopropyl or ethyl group which possibly facilitates dimerization. All three enthalpies of hydrogen bond formation are well below those quoted for the dimers of acetic acid (-26.7 kJ mol⁻¹ per H-bond⁵) and formamide (-29 kJ mol⁻¹⁶), while the entropy changes are comparable.

Table 1. Calculated thermodynamic parameters and rotatory strengths for dimerization of chiral hydroxyamines according to equation (1).

| Compound ^a | $c^{\rm b}/{ m mol}{ m dm}^{-3}$ | $-\Delta H^{\circ}/kJ \text{ mol}^{-1}$ | $-\Delta S^{\circ}/J \mathrm{K}^{-1} \mathrm{mol}^{-1}$ | $R_{A^{c}}$ | $R_{A_2}^{c}$ | r^{d} |
|-----------------------|----------------------------------|---|---|-------------|---------------|------------------|
| (1) | 4.9×10^{-4} | 35.2 | 81 | -10 | 290 | 0.9990 |
| | 1.23×10^{-4} | 35.2 | 79 | -4 | 297 | 0.9995 |
| | 2.22×10^{-5} | 34.7 | 74 | -1 | 308 | 0.9991 |
| (2) | 5.8×10^{-4} | 42 | 113 | 5 | 409 | 0.9985 |
| | 4.6×10^{-5} | 40 | 99 | -3 | 371 | 0.9995 |
| (3) | 5.4×10^{-4} | 36 | 84 | 9 | 280 | 0.9998 |
| | 1.5×10^{-4} | 36 | 83 | -4 | 298 | 0.9994 |

^a The absolute configuration of the asymmetric carbon atom is R in (1) and (3) and S in (2). ^b Initial monomer concentration. ^c Calculated rotatory strength of monomer and dimer, respectively, in units of $\Delta \varepsilon$. ^d Correlation coefficient of regression analysis. Hydrogen bonded complexes of retinal Schiff bases have recently become a focus of attention concerning the photochemistry of these biologically important systems.⁷ With respect to the proton translocation postulated⁸ on the basis of i.r. evidence for the hydrogen bond formed between all-*trans*retinal Schiff bases and phenol, $-O-H \cdots N = \rightleftharpoons -O^{-} \cdots$ $H-N^{+}=$, we have found that in very dilute solutions at low temperatures the observed split Cotton effects we observe in our dimers coalesce giving way to long-wavelength absorptions. Whether these are due to (protic) impurities in the solution or present genuine proton translocations in the dimer is the subject of ongoing investigation.

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