Tetrahedron Vol 39, No 24, pp. 4201 to 4208, 1983
Printed in Great Britain

0040-4020/83 $3.00 + .00
Pergamon Press Ltd.

AN NMR AND SOLVATION STUDY OF ROTATIONAL ISOMERISM IN EPIHALOHYDRINS

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(*Received in the UK January* 1983)

Abstract—The ^{1}H NMR spectra of epifluoro, chloro- and bromohydrin have been analysed in a number of solvents of varying polarity. Ab initio and molecular mechanism calculations together with solvation theory allowed an analysis of the observed solvent dependence of the proton couplings in terms of the anti and gauche rotamers only, the syn rotamer being of very small population: The Gaüche-anti energy difference in the vapour is 0.1, 0.5 and 0.7 kcal mol^{-1} for the three compounds respectively, though these relative energies may be reversed in solutions in which the gauche form is relatively more stabilized. The trans-oriented vicinal coupling has values of 7.3, 8.4 and 9.1 Hz for F, Cl, and Br respectively. Only one long-range coupling showed a pronounced orientation dependence, due to an approximately planar zig-zag orientation in the gauche rotamer.

Any investigation of the intramolecular interactions between oxygen and other electronegative atoms (e.g. the halogens) is complicated by the problems of the oxygen valency and hydrogen bonding effects. For example, even such a simple molecule as 2-fluoro-ethanol has five non-equivalent conformations and to-date, despite numerous investigations[1] there is no knowledge of the relative energies of most of these conformers, though the most stable one is known. One method of by-passing these problems is to form a cyclic ether, of which the ethylene oxides are the simplest case. Here we wish to examine, both theoretically and experimentally, the conformational isomerism and hence oxygen–halogen interactions in the epi-halohydrins (Fig. 1).

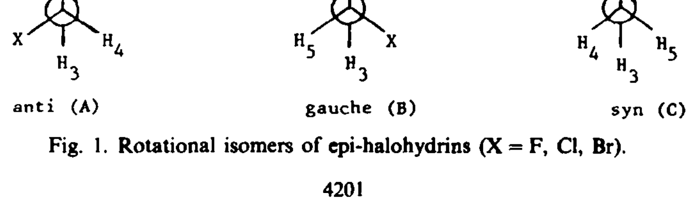
The compounds have been the subject of a mumber of investigations, by various physical methods. Despite some early reports,[2] there is now general agreement that there are three rotamers about the C·CH$_2$X bond (Fig. 1), but each investigation has used a different nomenclature for these rotamers. We will convert these into the nomenclature shown in Fig. 1.

Fujiwara *et al.*[3,4] analysed the microwave spectrum of epifluoro and epi-chloro hydrin. In both compounds, transitions from all three rotamers were observed, and the use of a model geometry allowed the determination of the torsional angles (X.C.C.H) as 60, 170 and 310° for the anti, syn and gauche forms.

From this identification the most stable form for the epifluorohydrin was shown to be the gauche form, with dipole moment 3.08 (±0.02) D, and relative energy (with respect to the syn and anti forms) of 400 (±200) cm^{-1}.[3]

The relative energies of the syn and anti forms were not obtained, and in a similar investigation of epichlorohydrin[4] the relative energies of the three rotamers could not be determined. IR measurements of the liquid and solid phases of epichlorohydrin identified two rotamers, one less polar than the other, based on the intensity variation of certain transitions with respect to solvents of differing dielectric constant.[5]

These compounds have been investigated by ^{13}C[6] and more extensively by ^{1}H NMR, partly due to the very complex proton spectra they give. At lower applied fields (< 100 MHz) the spectra are often a strongly coupled five spin system requiring iterative computer analysis to solve them. In addition, as the observed couplings are very dependent on the polarity of the medium (see later) comparison between the results of different investigations is not always straightforward. MacDonald and Schaeffer[7] gave the complete analysis of the ^{1}H NMR spectrum of epichlorohydrin in benzene and acetonitrile and following from this MacDonald and Reynolds[8] recorded the dipole moments and NMR parameters of all the epihalohydrins (X = F, Cl, Br, I) in benzene. They noted a gradual increase in the population of the anti rotamer on going from F→Cl→Br→I which was



anti (A) gauche (B) syn (C)

Fig. 1. Rotational isomers of epi-halohydrins (X = F, Cl, Br).

largely at the expense of the syn form, the gauche form remaining a constant fraction. Thomas,[9] in a detailed analysis of the epifluorohydrin spectrum in solvents of varying polarity, came to similar conclusions, with the gauche rotamer the most stable form in all solvents, the proportions of the others varying with solvent polarity. In all these investigations the analysis of the rotamer populations was qualitative, based on the observed changes in the couplings with solvent, not quantitative. We present here a quantitative analysis of the rotamer populations in solution, based on the application of solvation theory to the observed coupling constants in the different solvents. This enables the relative rotamer energies to be obtained, both in solution and (by extrapolation) in the vapour state and these latter values can then be compared with the results of theoretical investigations.

Theoretical study

As the analysis of the experimental results derives in some measure from the theoretical results, it is convenient to consider these first.

The relative rotamer energies of the epi-fluoro and epichloro hydrins were first calculated by *ab initio* quantum mechanics using the GAUSSIAN 70 program at the STO-3G level of approximation.[10] An initial model geometry was taken consisting of the microwave geometry of ethylene oxide[11] and propylene oxide[12] together with $CH_2F(Cl)$ geometries from the corresponding ethyl compounds.[13] The resulting geometries (Fig. 2) are very similar to those used by Fujiwara *et al.*[3,4] in their investigations.

For the fluoro compound an energy minimization was performed varying the $CH–CH_2F$ bond length and also the H–C–C–F. torsional angle. The results from this procedure are given in Table 1. For the chloro compound it was considered more appropriate to vary the C–C–Cl bond angle and the H–C–C–Cl torsional angle and the results are also given in Table 1.

It can be seen that at the STO-3G level, the *ab initio* calculations support the existence of the three rotamers (Fig. 1). The C–C bond length in the fluoro compound minimises at 1.54Å, the classical C–C single bond length, rather than the 1.51 (± 0.02) Å of propylene oxide. The torsional angles obtained show only small deviations from the classical values, presumably due to the small steric effects between the fluorine atoms and the epoxide ring, and this interpretation is supported by the calculated rotamer energies, which are to within the accuracy of the calculations, all of equal energy.

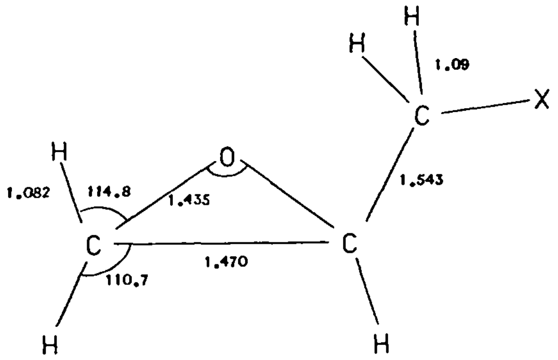


Fig. 2. Epihalohydrin geometry. X = F C.F. 1.385 Å, ∠C.C.F 109.28° X = Cl C.Cl 1.77Å, ∠C.C.Cl 111.0°, X = Br C.Br 1.93Å, ∠C.C.Br 111.0.

The results for the chloro compound show that in this case the syn rotamer is of appreciably higher energy than the other forms. The calcuated torsional angle of 194° suggests that this higher energy is due to steric repulsion between the chlorine and H_1 (Fig. 1), and the Cl–H distance of 2.63 Å is well within the sum of the Van der Waals radii of the two atoms (*ca* 3.0 Å).

The rotamer energies were also calculated by the molecular mechanics program MODELS,[14] as this gives both the relative rotamer energies in the vapour state and also the solvent dependence of the rotamer energies. The *ab initio* geometries (above) were used, iterating on the H–C–C–X torsional angle only.

The calculations include both the polar and steric interactions of the non-bonded atoms and thus a knowledge of the appropriate atomic charges to use is required. A scheme of calculating the atomic charges for use in such molecular mechanics calculations has been given recently.[15] This scheme incorporated the atomic orbital electronegativity and polarisability of the atoms involved, but was parameterised only for the haloalkanes. In order to extend this to the epoxy ring it is necessary to include the oxygen atom explicitly. As the hybridisation of the oxygen in the epoxy ring is not obvious, and the orbital electronegativity is a function of the hybridisation,[16] it is simplest to merely adjust the oxygen electronegativity so as to give the correct dipole moment (1.88 D) for ethylene oxide. With this single amendment the atomic charges and hence dipole moments of all the compounds studied here can be calculated and these are given in Table 1. It is encouraging to note the agreement between the observed dipole moments of propylene oxide (1.90–1.98 D)[17] and gauche eqifluorohydrin (3.08 D)[3] with the calculated values of 1.91 and 3.13 D. This lends support to the validity of the solvation calculations, which are based on these atomic charges. In contrast the dipole moments calculated on the *ab initio* treatment (Table 7) are for gauche epifluorohydrin much less than the observed values, and thus the atomic charges obtained from such treatments can not be used successfully in the solvation calculations.

The MM calculated rotamer energies (Table 1) compare reasonably with the corresponding *ab initio* figures. In the fluoro compound the anti-rotamer is still the most stable form, with the gauche form of somewhat higher energy. In the chloro compound the same order of rotamer stability is obtained as for the *ab initio* results, but the actual values are larger; indeed, the syn rotamer could be considered as of negligible population ($\Delta E > 3$ kcal mol^{-1}). The epibromohydrin results are virtually identical to the chloro compound, which is not surprising.

The solvent dependence of the rotamer energies

The relative rotamer energies in any solvent of given dielectric content are also calculated by the program MODELS and these relative energies are also given in Table 1. The solvation theory used has

Table 1. Calculated rotamer energies and molecular parameters for epihalohydrins[a]

$X = F$[b]		STO-3G			MODELS[d]		
		anti	gauche	syn	anti	gauche	syn
dipole moment (D)		0.37	2.18	2.06	0.37	3.13	2.76
torsional angle (°)		62	308	184	64	304	176
rel.energy	$\varepsilon = 1.0$	0.0	0.1	0.3	0.0	1.1	0.5
($kcals.mole^{-1}$)	2.2				0.0	0.7	0.1
	4.9				0.0	0.3	-0.2
	32.0				0.0	-0.2	-0.5
$X = Cl$[c]							
dipole moment		0.94	3.20	3.03	0.36	3.13	2.95
torsional angle		68	304	194	65	303	187
rel.en.	$\varepsilon = 1.0$	0.0	0.6	2.4	0.0	0.9	3.9
	2.2				0.0	0.6	3.6
	4.9				0.0	0.3	3.3
	32.0				0.0	-0.2	2.8
$X = Br$							
dipole moment					0.39	3.10	2.92
torsional angle					63	304	187
rel.en.	$\varepsilon = 1.0$				0.0	1.0	3.4
	2.2				0.0	0.8	3.1
	4.9				0.0	0.4	2.8
	32.0				0.0	0.0	2.4

a. Geometries from Figure 2 except where indicated otherwise.
b. $CH.CH_2F$ bond 1.54Å.
c. ∠C.C.Cl
d. With E(O) 13.54.

been described in full previously,[17] and need not be repeated here. It should, however, be noted that the solvent dependence of the rotamer energies is only a function of the solvent dielectric constant, and of the dipole (and quadrupole) moments of the individual rotamers. Thus, although the calculated values of the rotamer energies in the gas phase are critically dependent on the steric potentials, force-constants and geometries used in the calculations this is not the case for the solvation dependence, i.e. the difference between the vapour state and solution energies. This will be utilised later on.

The results in Table 1 show that the gauche and syn rotamers are considerably stabilised in solution compared to the trans form due to their much larger dipole moments. In the fluoro compound these are calculated to be the most stable forms in highly polar media. In the chloro and bromo compounds the solvation energy is insufficient to overcome the steric repulsion in the syn form and this is calculated to be a very high energy rotamer in all solvents. The gauche rotamer does become of comparable energy to the trans form in polar media. These results are of importance in the analysis of the experimental values of the coupling constants in the different solvents

EXPERIMENTAL AND SPECTRAL ANALYSIS

The epifluoro, chloro and bromo hydrin were commercial samples (Aldrich Chemical Company Limited) and used unchanged. There was no evidence of impurities in the NMR spectra. The ^1H NMR spectra of the compounds were obtained for 1% (0.1 M) solutions in various solvents of different polarity on Bruker WH.250 and (in two cases) Bruker WM.400 spectrometers. Typical conditions for the WM.250 were probe temperature 23°, S.W. 1000 Hz, A.T. 8 sec. digitisation 0.1 Hz/point, number of scans *ca* 100. Gaussian multiplication of the F.I.D. was used to increase the resolution, which was sufficient in most cases to resolve all the allowed transitions.

The molecules contain five non-equivalent protons and, therefore, the spectra are in the general case ABCDE analyses, with the addition of the coupled $X = F$ nucleus in the epifluorohydrin. All the spectra were analysed using the LAOCOON. 3 programme,[18] which is of use even for first-order spectra as the r.m.s. error and probable errors provide a measure of the accuracy of the measurement.

At the field strengths used here, many of the spectra were first order and could be analysed without difficulty.

Table 2. Chemical shifts (δ) and coupling constants (Hz) in epifluorohydrin

SOLVENT	CCl_4 [a]	CCl_4 [b]	$CDCl_3$ [b]	LIQUID [b]	CD_3CN [b]
δ_1	2.555	2.557	2.663	2.581	2.641
δ_2	2.751	2.758	2.854	2.783	2.835
δ_3	3.119	3.143	3.249	3.203	3.257
δ_4	4.291	4.207	4.288	4.159	4.215
δ_5	4.465	4.566	4.651	4.683	4.742
J_{12}	5.22	5.14	4.90	4.97	4.85
J_{13}	2.49	2.55	2.64	2.65	2.59
J_{14}	-0.29	-0.25	-0.20	-0.25	-0.16
J_{15}	-0.30	-0.25	-0.31	-0.25	-0.25
J_{1F}	-1.19	-1.32	-1.22	-1.57	-1.63
J_{23}	4.06	4.20	4.25	4.29	4.27
J_{24}	0.31	0.15	0.1	0.1	0.0
J_{25}	0.00	0.15	0.0	0.0	0.0
J_{2F}	3.32	3.60	3.67	3.87	3.96
J_{34}	5.42	5.83	5.88	6.37	6.51
J_{35}	3.26	2.73	2.56	2.20	2.16
J_{3F}	11.12	11.74	12.25	12.00	11.85
J_{45}	-10.45	-10.57	-10.75	-10.81	-10.82
J_{4F}	47.23	47.18	47.17	47.35	47.15
J_{5F}	47.71	47.84	47.61	47.77	47.99

a. 1% solution, all probable errors < .005 Hz, r.m.s. error 0.02 Hz.
b. 10% solutions, from reference 9.

Thomas[9] has given the complete analyses of epifluorohydrin at *ca.* 10% concentration in various solvents, thus we recorded here this spectrum in a much more dilute (1%) carbon tetrachloride solution. The spectrum was first-order at the field strength used (400 MHz) and the results of this analysis are given in Table 2, together with those of Thomas.

The relative signs of the couplings are not given in these analyses, and are taken here from the results of previous investigations. Macdonald and Schaeffer[7] and MacDonald and Reynolds[8] from extensive tickling experiments found that the cisoid long range couplings (J_{14}, J_{15}) are negative, whilst the transoid couplings (J_{24}, J_{25}) either zero or positive, and we use their results henceforth. For the chloro compound the spectra are again slightly perturbed first-order spectra, except for the spectrum in $CDCl_3$ solution. In this case the diastereotopic methylene protons (H_4, H_5, Fig. 1) become very closely coupled and the spectrum is a deceptively simple one.[18b] The analysis was performed as recommended in such cases, by incorporating the value of J_{45} obtained from the other solvents and not iterating on this coupling. With this procedure the iteration proceeded normally. The resolution of the epichlorohydrin spectrum in CD_3CN was insufficient to resolve the long range couplings and Table 3 includes the results of a previous analysis in this solvent.[7]

The epibromohydrin analysis was somewhat more complex as the methine proton (H_3) and the methylene protons (H_4, H_5) were often strongly coupled, thus this spectrum is an ABCXY system even at 250 MHz. By trial and error procedures the analysis of the spectra in all the four solvents used was performed to give reasonable values of the r.m.s. and probable errors (Table 4).

The spectral analysis does not of course assign the individual methylene protons H_4 and H_5 and the assignments given in the Tables 2–4 for these protons follow those of previous investigations and also the expected dependence of the couplings on the solvent polarity (see later).

RESULTS AND DISCUSSION

The values of the chemical shifts and couplings within the epoxy ring are in complete accord with those of previous investigations.[7-9] Those involving the methylene protons H_4, H_5 are also in agreement with previous investigations, the differences being due to the different solvents and for the non-polar solvents in particular the lower concentrations used here.

We wish to determine the rotamer populations and relative energies from the observed solvent dependence of the couplings. The observed couplings are the weighted averages of the couplings in the

Table 3. Chemical shifts (δ) and coupling constants (Hz) in epichlorohydrin

SOLVENT	CCl_4[a]	CS_2	$CDCl_3$[a]	CD_2Cl_2	CD_3CN
δ_1	2.471	2.347	2.697	2.658	2.656
δ_2	2.705	2.571	2.905	2.860	2.833
δ_3	3.045	2.921	3.252	3.210	3.203
δ_4	3.515	3.333	3.583	3.492	3.462
δ_5	3.266	3.219	3.578	3.676	3.776
J_{12}	5.09	5.08	4.81	4.85	4.90
J_{13}	2.36	2.30	2.49	2.46	2.44
J_{14}	-0.29	-0.31	-0.34	-0.32	0.00 (-0.30)[c]
J_{15}	-0.29	-0.19	-0.28	-0.24	0.00 (-0.26)[c]
J_{23}	3.76	3.78	3.91	3.94	3.97
J_{24}	0.81	0.69	0.35[b]	0.42	0.00 (0.39)[c]
J_{25}	0.00	0.00	0.27[b]	-0.01	0.00 (0.03)[c]
J_{34}	5.23	5.56	5.73	6.45	6.92
J_{35}	5.90	5.37	5.00	4.31	3.83
J_{45}	-11.50	-11.51	-11.50	-11.80	-11.79
r.m.s.[d]	.024	.053	.033	.041	0.031

a. 400 MHz.
b. deceptively simple (see text).
c. from reference 7
d. all probable errors <0.01 Hz, except b (0.05Hz).

Table 4. Chemical shifts (δ) and coupling constants (Hz) in epibromohydrin

SOLVENT	CCl_4	$CDCl_3$	CD_2Cl_2	Ac-D6
δ_1	2.367	2.677	2.646	2.677
δ_2	2.667	2.952	2.912	2.890
δ_3	3.011	3.277	3.240	3.241
δ_4	3.276	3.437	3.365	3.409
δ_5	2.964	3.352	3.418	3.589
J_{12}	5.043	5.084	4.886	5.088
J_{13}	2.336	2.399	2.418	2.404
J_{14}	-0.300	-0.078	-0.023	-0.041
J_{15}	-0.108	-0.016	-0.009	-0.002
J_{23}	3.786	3.862	3.880	3.899
J_{24}	0.898	0.748	0.625	0.500
J_{25}	-0.084	-0.125	-0.099	-0.013
J_{34}	5.331	5.652	5.817	6.840
J_{35}	6.611	5.784	5.777	4.680
J_{45}	-10.460	-10.481	-10.561	-10.708
rms[a]	0.045	0.020	0.018	0.025

a all probably errors < 0.02Hz.

Table 5. Rotamer energy differences (kcal mol^{-1}) and coupling constants (Hz) in epihalohydrins

	ANTI (A)			GAUCHE (B)		
	F	Cl	Br	F	Cl	Br
E^V	0.0	0.0	0.0	0.1	0.5	0.7
J_{34}	1.4	3.0	2.6	7.3[a]	8.4[b]	9.1[c]
J_{35}	7.3[a]	8.4[b]	9.1[c]	1.3	2.1	2.1
J_{24}	1.5	1.5	1.4	-0.2	-0.2	0.0
J_{1F}	0.4	-	-	-2.0	-	-
J_{2F}	0.8	-	-	4.5	-	-

a,b,c, assumed equal (see text).

individual rotamers, i.e.

$$\left.\begin{aligned} J_{obs} &= \sum_{i=A,B,C} N_i J_i \\ \text{where } \textstyle\sum N_i &= 1 \\ \text{and } N_j/Nj &= \exp\left(-\Delta E^s_{ij}/RT\right). \end{aligned}\right\} \qquad (1)$$

ΔE^s_{ij} equals $E^s_i - E^s_j$, the energy difference between rotamers i and j in the solvent s. These energy differences in any solvent of dielectric constant (ϵ) can be related to the corresponding vapour phase energy differences by the solvation calculations, i.e.

$$\Delta E^s = \Delta E^V - f(\epsilon) \qquad (2)$$

where $f(\epsilon)$ is a function of the solvent dielectric constant and of the rotamer dipole and quadrupole moments, and this expression can be calculated for any pair of rotamers and solvent. Combining eq (1) and (2) allows the observed rotamer couplings to be calculated in any solvent from the couplings in the individual rotamers and the vapour state energy differences and thus in principle an iterative analysis on the solvent data collected here should give both the rotamer couplings and the vapour state energy differences.

It is convenient in practice to consider first the epichloro and epibromohydrin data. In these compounds both the *ab initio* and the molecular mechanics calculations agree (Table 1) that the syn isomer is of very small population in all solvents studied, thus we may to a good approximation neglect this rotamer completely. Equations (1) and (2) now become

$$\left.\begin{aligned} J_{obs} &= N_A J_A + N_B J_B \\ 1 &= N_A + N_B \\ N_A/N_B &= \exp\left(-\Delta E^s/RT\right) \\ \Delta E^s &= \Delta E^V + f(\epsilon). \end{aligned}\right\} \qquad (3)$$

The variation in J_{obs} with solvent dielectric constant is thus a function only of the three variables J_A, J_B and ΔE^V ($E_B{}^V - E_A{}^V$). For this case a computer program (BESTFIT) has been described to analyse the observed solvent dependence.[19] The program starts with a given value of ΔE^V and from this calculates from eq (3) the value of ΔE^S and hence N_A and N_B for each solvent. These values in turn when combined with the observed couplings produce a two parameter fit in the unknowns J_A and J_B in N equations where N is the number of solvents used, which is solved by standard methods to give the best fit values of J_A and J_B and the r.m.s. error in $J_{obs} - J_{calc}$. A range of values of ΔE^V can be input and the output searched for the appropriate values of J_A and J_B and/or the best fit. The method can be used for any coupling provided that the variation in the observed coupling with solvent is due to the change in the rotamer populations and not to any intrinsic solvent dependence. The definition of the results is greatest for couplings with the largest variation with solvent, and thus the most appropriate couplings to consider are the vicinal couplings J_{34} and J_{35}.

The assignment of J_{34} and J_{35} as given in Tables 3 and 4 follows from the predicted solvent dependence of the couplings. With the gauche rotamer becoming more populated in the polar media J_{35} varies from a trans oriented to a gauche coupling and J_{34} vice versa, thus J_{35} decreases with increasing solvent polarity and J_{34} increases. These couplings were input into BESTFIT and the value of ΔE^V searched for the best solution. The resulting values of the rotamer couplings vary greatly with the value of ΔE^V, but the r.m.s. error only slightly. For example, in the chloro case over a 2 kcal mol^{-1} range of ΔE^V the r.m.s. error for J_{34} calculated versus observed only varied from 0.16 to 0.14 Hz, and this variation is not sufficiently well defined to give an accurate value of ΔE^V. Fortunately, in these systems there is a very simple alternative. J_{35} in the anti isomer is a trans oriented coupling and so is J_{34} in the gauche isomer, and to a good approximation these couplings would be expected to be of similar magnitude. As the couplings are treated quite separately in the analysis this provides a simple method of defining ΔE^V. This gave the values in Table 5. Having obtained the values of ΔE^V, the remaining couplings to H_4 and H_5 may be analysed immediately. However, it is clear from the results that the cisoid long range couplings J_{14},J_{15} do not show any systematic variation with solvent. For epichlorohydrin the values are constant to within the experimental error, $J_{14} - 0.31(\pm 0.01)$ Hz, $J_{15} - 0.25(\pm 0.03)$ Hz, whilst for the bromo compound the resolution was not sufficient to resolve them for all the solvents except CCl_4. Also the values of J_{25} are in all cases essentially zero (note the deceptively simple analysis of the chloro compound in $CDCl_3$, Table 3). The only long range coupling showing a pronounced systematic solvent dependence is J_{24} and using the values of ΔE^v in Table 5, together with the observed data gives the values in Table 5.

The epifluorohydrin results are more complex to analyse, as there is no good reason to assume in this case that the syn rotamer is of negligible population. It should be noted here that there is a marked discrepancy between the calculated values of the rotamer energy differences in the vapour phase, which are small, but favour the anti rotamer (Table 1), and the results of the microwave investigation[3] which found the gauche form to be predominant. Similar discrepencies between observed and calculated energies are well known for compounds with vicinal electronegative atoms, such as oxygen and fluorine.[1c] In this analysis we may proceed by noting firstly that the dipole moments and hence solvation energies of the gauche (B) and syn (C) rotamers are very similar. For example, Table 1 shows that the energy difference $E_B - E_C$ only changes from 0.61 kcal mol^{-1} in the vapour phase to 0.37 kcal mol^{-1} in acetonitrile solution. Thus, as far as the solvation dependence of the couplings is concerned the syn and gauche forms may be combined into one composite form (BC), in which the couplings are weighted averages of those in the separate rotamers.

The second point to note is the actual solvent dependence of the couplings to the methylene hydrogens. The sum $J_{34} + J_{35}$ has the value $J_g + J_t$, $J_t + J_g$ and $2J_g$ in the anti, gauche and syn rotamers respectively (Fig. 1). Thus, this sum will be independent of the variation of the anti and gauche rotamers, but change appreciably with any change in the population of the syn form. The observed values of $J_{34} + J_{35}$ are 8.68, 8.44, 8.57 and 8.67 Hz, in the four solvents, showing no systematic change with solvent polarity. As the couplings themselves are varying considerably, this suggests that the syn rotamer is of very small population in all the solvents. The same conclusion emerges from an analogous analysis of J_{3F} which again is independent of solvent and has a value characteristic of a gauche oriented $^3J_{HF}$ coupling.[20]

The analysis of the solvent dependence of the vicinal couplings using the BESTFIT programme follows from the above considerations. We consider two extreme cases. The first is to neglect entirely the syn rotamer, exactly as in the chloro and bromo compounds. An identical analysis to those using the vicinal couplings J_{34} and J_{35} gives the values of ΔE and of the rotamer couplings shown in Table 5.

The opposite extreme is to assume the syn and gauche forms have equal energy, and therefore population in all the solvents. In this case the analysis is as before, except that the statistical weight of the composite (B, C) rotamer is now 2. As also there is no simple identity analogous to $J^B_{34} = J^A_{35}$, we merely took the value of J^A_{35} to be *ca* 7–8 Hz. The BESTFIT solution then gives $\Delta E(E_A - E_{B,C}) - 0.3$ kcal mol^{-1}, $J^{B,C}_{35}$ 1.4 Hz, J^A_{34} 1.0 Hz and $J^{B,C}_{34}$ 7.1 Hz. These values are reasonable except for the value of $J^{B,C}_{34}$ which equals $\frac{1}{2}(J_t + J_g)$, from Fig. 1. On any basis, the value of 7.1 Hz is much too high for this average coupling and this demonstrates that this alternative analysis is not valid for epifluorohydrin, and that in this compound, as in the other cases, the population of the syn rotamer is very small. Using the value of ΔE and the observed values of J_{24}, J_{lF} and J_{2F} (Table 2), allows the rotamer couplings in these cases to be obtained, and these are also given in Table 5.

The major result emerging from the above analysis is the low population (if any) of the syn rotamer in all the compounds studied. This agrees with the conclusion of Thomas for epifluorohydrin,[9] but not with those of Macdonald and Reynolds[8] who regarded the syn form as the second major conformer, after the gauche form. A further check of our analysis may be provided by the results of these latter workers, who gave a detailed analysis of all the epihalohydrin spectra in benzene solution, as well as determining their dipole moments in the same solvent. Using the values of the rotamer couplings J_{34}, J_{35} given in Table 5 with the observed couplings from reference 8 gives the population of the anti isomer in benzene solution as 20.9 ± 0.5, 43 ± 1 and $46 \pm 1\%$ for the fluoro, chloro and bromo compounds respectively. Furthermore, the calculated values of the conformer dipole moments (Table 1) may be used similarly with the observed dipole moments in benzene solution to give corresponding values of 28, 47 and 51%. The two sets of values are in very reasonable agreement, considering the possible existence of some of the syn form in the fluoro compound and also that the NMR measurements were obtained in 10 mol% solutions whereas the dipole moment determinations were extrapolated to infinitely dilute solutions. Increasing the solute concentration increases the dielectric constant and hence the percentage of the gauche isomer, exactly as observed. Thus, the detailed results of reference 8 may be quantitatively interpreted on the basis of the analysis given here.

Our analysis is also supported by IR data on epichlorohydrin,[5] for which only two rotamers were observed in the liquid and solid phases, one less polar than the other. However, Fujiwara and co-workers obtained the microwave spectra of all three rotamers of epifluoro and epichloro hydrin, although no values of the relative energies of the syn forms were given. It would be of interest to perform a related measurement (e.g. electron diffraction) to determine the relative populations of the three rotamers in the vapour phase.

The values of the rotamer couplings obtained (Table 5) are of some interest. The vicinal couplings show the expected increase in the trans oriented coupling (J^A_{35}, J^B_{34}) on going from $F \rightarrow Cl \rightarrow Br$, but the guache oriented couplings J^A_{34} and J^B_{35} show no systematic trends, due perhaps to the presence of some of the syn rotamer in the fluoro compound. On electronegativity grounds alone J^A_{34} would decrease and J^B_{35} would remain constant in going from $F \rightarrow Cl \rightarrow Br$.[21]

The long-range couplings show a considerable change in their orientation dependence. The only positive long-range coupling is J^A_{24} and this is the nearest to the planar zig-zag orientation required. In contrast, J^B_{24} is not significantly different from zero and the long-range couplings H_1 are negative and do not have any significant orientation dependence.

Acknowledgements—We acknowledge an SERC grant for the purchase of the Bruker WM.250 spectrometer, the high-field SERC service and the help of Dr. B. E. Mann and Dr. C. Spencer at the University of Sheffield, and B. R. acknowledges an L.E.A. Grant (Wirral Education Authority).

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