

Comparison of Carbon-13 Nuclear Magnetic Resonance Methods for the Analysis of Multiple Partially Deuteriated Products from Catalytic Reactions: Heptan-1-ol and 2-Methylpropanol†

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Products from the hydrocarbonylation of hex-1-ene or prop-2-en-1-ol using H_2-CO or D_2-CO in EtOH or EtOD have been analysed using ^{13}C NMR techniques. Where there are up to four isotopomers in the products, analysis of β -shifted resonances in the $^{13}C-\{^1H\}$ NMR spectrum can give enough information for quantification of all isotopomers. Using prop-2-en-1-ol, D_2-CO and EtOH, the 2-methylpropanol produced is a mixture of 16 different isotopomers. These can be individually quantified by analysis of the $^{13}C-\{^1H, ^2D\}$ NMR spectrum. In particular, the resonance from the methyl C atom shows β and γ shifts, the latter being different for different types of γ -D atom. These analytical methods are shown to be superior to other possibilities including 1H NMR and mass spectrometry.

Many techniques have been used to study the mechanisms of catalytic reactions and amongst these, isotopic labelling studies, usually using 2D , ^{13}C , ^{14}C or ^{18}O , have figured prominently. For ^{14}C , analysis generally involves GLC of the products with a scintillation counter detector,¹ whilst mass spectrometry is the preferred method for the other isotopes. These techniques give important information about the products in which the isotopic labels occur, as well as about the number of labelled nuclei in each product. However, they can give information about the exact position of the label in the molecule and about the extent of incorporation of the label into that particular site only in very favourable circumstances.

In studying mechanisms of biological systems, chemists have required to know the exact positions of incorporation of labelled atoms, especially 2D , and the extent of deuteration at particular sites. They have, therefore, developed NMR techniques which can effectively be used to tackle both of these problems.² These techniques have not been extensively employed in the analysis of products from reactions catalysed by soluble metal complexes, although labelling studies can be very important in elucidating the mechanisms of these reactions.

During the course of studies³⁻⁵ of the hydrocarbonylation of alkenes using rhodium trialkylphosphine catalysts, which lead to the formation of alcohols rather than the expected aldehydes under mild conditions, as well as the formation of similar products in reactions using *e.g.* ethanol as the hydrogen source,⁶ we have carried out various labelling studies in order to obtain mechanistic information. In many cases, mixtures of different labelled products with partial deuteration at a variety of different sites are obtained. This presented a considerable analytical challenge, since we required to know the amounts of each of up to 18 different isotopomers present in the product mixture. In this paper we compare various ^{13}C NMR techniques for the quantitative analysis of these mixtures.

Results and Discussion

$^{13}C-\{^1H\}$ NMR Spectra.—(i) *Technique.* Replacing an H atom attached to carbon in a compound with a 2D atom leads to various effects on the 1H , 2D and ^{13}C NMR spectra. Most obviously, the signal from that proton in the 1H NMR

spectrum is removed and couplings to that proton are replaced by couplings to 2D [1:1:1 triplet, $J(X-D) \approx \frac{1}{6} J(X-H)$]. A new signal is observed in the 2D NMR spectrum from the introduced 2D atom. Changes in the $^{13}C-\{^1H\}$ NMR spectrum are often easier to identify, especially if the spectrum is complex, and can give better quantitative information.

The resonance from the carbon atom to which the new D atom is attached splits into a 1:1:1 triplet but also shifts (the alpha shift) by *ca.* 0.4 ppm to high field. Two deuteriums on the same carbon atom give a 1:2:3:2:1 quintet shifted further by *ca.* 0.4 ppm. Although these changes show qualitatively which carbon atoms have been deuteriated, they cannot easily be used to provide quantitative data about the extent of deuterium incorporation because the Overhauser enhancements of the signals from the CH_2 , CHD and CD_2 carbon atoms are different. The signals also overlap with one another because often the C-D coupling constant is similar to the α shift (at least at 75.5 MHz observation). Although the Overhauser problem can be overcome by using different pulse sequences or relaxation agents, a simpler approach to the quantitative analysis of these signals involves analysis of the resonance of the carbon atoms β to the 2D atom. These resonances do not show any coupling to deuterium, but they are shifted (β shift) by *ca.* 0.05–0.12 ppm to high field for each β -deuterium. Since β couplings are generally very small, the Overhauser enhancements of the carbon atom β to the H or D atom are very similar so that the relative areas of these signals can be used to obtain quantitative information about the amount of deuterium at any position in the molecule.

(ii) *Analysis of heptanol.* As a simple example, Table 1 gives the chemical shifts of the different carbon atoms of heptanol. These are in good agreement with calculated⁷ and literature⁸ values. Also shown are the values for heptanol exchanged with D_2O , which show a small shift to high field for C^1 and C^2 . We have reported³ that $[RhH(PEt_3)_3]$ acts as a catalyst precursor for the production of heptanol and 2-methylhexanol from hex-1-ene, CO and hydrogen in ethanol. In this we have shown that heptanal and 2-methylhexanal are the products after short reaction times but that these aldehydes are hydrogenated to the corresponding alcohols if the reaction is prolonged.³ Having shown independently that the same catalytic system under H_2-CO will hydrogenate heptanal to heptanol in ethanol solvent at a rate similar to that of the hydrocarbonylation reactions,⁴ we were interested to discover whether the production of

† Non-SI unit employed: bar = 10^5 Pa.

Table 1 Carbon-13 NMR data for C₇ alcohols in CDCl₃ at 298 K

Sample	C ¹	<i>J</i> (C-D)/ Hz	C ² ^a	C ³	C ⁴	C ⁵	C ⁶	C ⁷ ^b
Heptanol (authentic)	62.72		32.81	25.88	29.27	31.97	22.72	14.11
Heptanol exchanged with D ₂ O	62.45		32.74	25.94	29.34	32.03	22.77	14.14
2-Methylhexanol (authentic)	68.20		35.81	33.01	29.33	23.08	14.12	16.67
Hex-1-ene + CO-D ₂ in EtOH								
heptanol	61.84 (qnt)	21.6	32.52	25.51 (t) ^c	29.24	32.01	22.77	14.13
2-methylhexanol	67.25 (qnt)	21.3	35.57	33.05	29.41	23.15	14.13	16.38
Heptanal								
+ CO-D ₂ in EtOH	62.39		32.82 (0.58)	26.02	29.41	32.11	22.83	14.14
+ CO-H ₂ in EtOD	62.02 (t)	21.4	32.71 (0.42)					
+ CO-H ₂ in EtOD	62.62		32.78 (0.79)	25.91	29.31	32.01	22.75	14.12
+ CO-D ₂ in EtOD	62.25 (t)	21.7	32.67 (0.21)					
+ CO-D ₂ in EtOD	62.03 (t)	21.5	32.69	25.99	29.40	32.09	21.81	14.15

^a Relative intensity in parentheses. ^b Defined as the methyl group of 2-methylhexanol. ^c *J*(C-D) 19.1 Hz.

alcohols from the reaction carried out in ethanol was also sequential *via* the aldehydes or whether some other reaction pathway operated. A series of labelling studies was therefore performed. These involved carrying out various reactions, separating the C₇ alcohols by fractional distillation and analysing the products by ¹³C (and ¹H) NMR spectroscopy. The results concerning the linear (heptanol) product will be described, although those for 2-methylhexanol are exactly analogous and are included in Table 1.

Using D₂ in place of H₂ in the hydrocarbonylation reaction carried out in EtOH leads almost exclusively to BuCHDCH₂-CD₂OH/D. This is clear from the observation of (a) a quintet resonance (*J*_{CD} = 21.6 Hz) for the alkoxy C atom (C¹) shifted by 0.88 ppm* (2 × α shifts) from the resonance of the equivalent C atom in unlabelled heptanol, (b) a triplet resonance from C³ (*J*_{CD} = 19.1 Hz) shifted by 0.37 ppm (1 × α shift), (c) a single major resonance (≈ 90%) for C² shifted by 0.29 ppm (3 × β shift) and (d) a single resonance for C⁴ shifted by 0.10 ppm (1 × β shift), see Table 1. The hydroxy proton is a mixture of H and D because of exchange with the alcohol solvent.

Using D₂-CO in place of H₂-CO in the hydrogenation of heptanal catalysed by [RhH(PET₃)₃] in ethanol gives a C₇ alcohol fraction for which the data are again collected in Table 1. The resonance from C¹ appears as a singlet for undeuteriated heptanol together with a triplet shifted by 0.37 ppm (1 × α shift) from the compound with one D atom on this carbon atom. The ratio of these two products can then be calculated from the relative intensities of the two signals from C², one in the place expected for heptanol (δ 32.82) and the other β-shifted by 0.11 ppm. The products can be unambiguously assigned as BuCH₂CH₂CH₂OH/D (58%) and BuCH₂CH₂CHDOH/D (42%). This somewhat surprising result shows that heptanal cannot be an intermediate on the pathway to heptanol in the hydrocarbonylation of hex-1-ene since, even if all of the heptanal formed in the first step were BuCHDCH₂CDO, hydrogenation of this material in EtOH with D₂ in the gas phase would give a mixture of BuCHDCH₂CD₂OH/D and BuCHDCH₂CHDOH/D, only the former of which is observed. We have used NMR studies of model systems⁴ to show that the mechanism probably involves protonation of an acyl intermediate to give a hydroxycarbene which frustrates the reductive elimination of aldehyde but rather leads directly to the alcohol as the primary reaction product.⁴

(iii) *Analysis of 2-methylpropanol-1-ol.* Hydrocarbonylation of prop-2-en-1-ol in ethanol using [Rh₂(O₂CMe₄)₄].2MeOH and PET₃ as the catalyst precursors gives butane-1,4-diol and

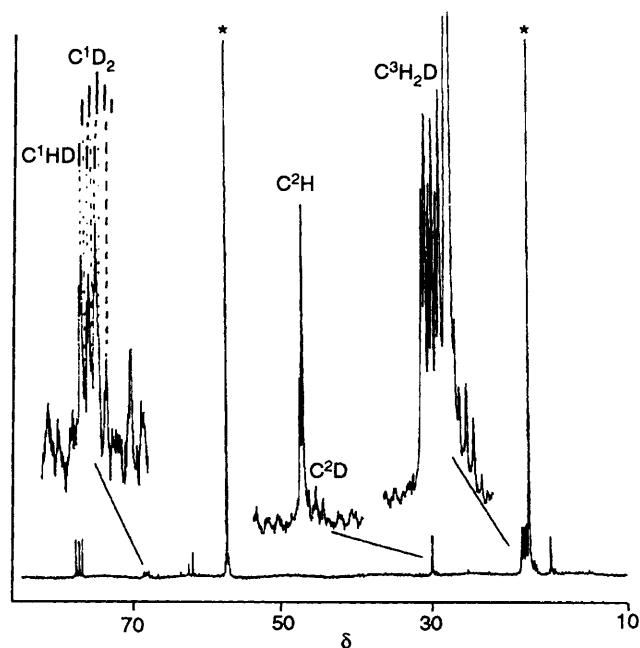


Fig. 1 The ¹³C-{¹H} NMR spectrum at 75.4 MHz of the fraction containing labelled 2-methylpropanol from hydrocarbonylation of prop-2-en-1-ol in EtOD using D₂-CO. The asterisk indicates ethanol impurity

2-methylpropanol (2:1 mol ratio under the conditions employed). The latter is an unexpected product since it formally arises from addition of methane across the double bond of the prop-2-en-1-ol. We have, therefore, carried out labelling studies to try to identify its origins. In Table 2 are listed the NMR parameters for the carbon atoms of 2-methylpropanol and the various labelled products obtained from hydrocarbonylation of prop-2-en-1-ol using D₂-CO in ethanol, H₂-CO in EtOD and D₂-CO in EtOD and of 2-methylpropanol obtained from hydrogenation of 2-methylpropanol under identical conditions.

The ¹³C-{¹H} NMR spectrum of 2-methylpropanol obtained from hydrocarbonylation of prop-2-en-1-ol in EtOD using D₂-CO is shown in Fig. 1. The resonance from C³ appears as two 1:1 triplets. Since each line of the triplet is of the same height, we can be certain that all of the C³ carbon atoms are CH₂D.† In other cases, where CH₃ is also present, the line to lowest field of each triplet is increased in intensity. From the relative ratios of the two triplets, which arise because of β-shifting of the

* For these calculations we have used the same values for δ for the C atoms of heptanol OH/D as those of C₇H₁₅OH since the D incorporation is fairly small (≈ 20%). Similar shifts have been reported previously.

† In the ¹³C-{¹H,²D} NMR spectrum weak resonances (≈ 9% of the total) from compounds containing CH₃ at C³ are observed but there is no evidence for CH₂ on C¹.

Table 2 The ^{13}C - $\{^1\text{H}\}$ (75.4 MHz) and ^1H NMR spectral data for 2-methylpropanol recovered from various reactions in CDCl_3 at 298 K

Sample	C^1		C^2		C^3		C^1H	C^2H	C^3H
	δ^a	$J(\text{C-D})/\text{Hz}$	δ^a	$J(\text{C-D})/\text{Hz}$	δ^a	$J(\text{C-D})/\text{Hz}$	δ	δ	δ
Authentic	69.51 (s)		30.96 (s)		19.14		3.33 (2)	1.77	0.90
Exchanged with D_2O	68.75 (s)		30.58 (s)		18.73			(spt, 1)	(d, 6)
2-Methylpropanol									
+ D_2 -CO-EtOH	68.78 (s)		30.61		18.77		3.33	1.75 (spt, ^b	0.88
			(s, 0.44)		(s, 0.88)		(d, ^b 1.2)	0.88)	(d, ^b 5.7)
	68.39 (t)	21.6	30.51		18.65				
			(s, 0.56)		(s, 0.12)				
+ H_2 -CO-EtOD	69.09 (s)		30.77		18.96		3.34	1.75	0.88
			(s, 0.82)		(s, 0.93)		(d, 1.74)	(spt, 0.93)	(d, 5.9)
	68.71 (t)	21.4	30.67		18.85				
			(s, 0.18)		(s, 0.07)				
+ D_2 -CO-EtOD	68.75 (s)		30.58		18.73		3.30	1.77	0.85
			(s, 0.04)		(s, 0.85)		(d, 0.96)	(sxt, 0.85)	(d, 5.7)
	68.36 (t)	21.4	30.49		18.62				
			(s, 0.96)		(s, 0.15)				
			30.25 (t)	18.4					
Prop-2-en-1-ol									
+ D_2 -CO-EtOH	68.86 (s)		30.66		18.75 (s ^c)		3.31	1.74	0.88
			(s, 0.016)				(d, 0.63)	(sxt, 0.95)	(t, 5.6) ^d
	68.47 (t)	21.4	30.55		18.64 (s ^c)				
			(s, 0.074)						
	68.09 (q)	21.8	30.47		18.22	19.2			
			(s, 0.253)		(t, 0.82)				
			30.39		18.37	19.2			
			(0.434)		(t, 0.18)				
			30.30						
			(s, 0.222)						
+ H_2 -CO-EtOD	69.0		30.67 (s)		18.84		3.32 (br d,	1.76	0.88
	(s, 0.59) ^e				(s, 0.63)		0.60)	(spt, 0.63)	(d, ^b 7.3)
	68.9		29.93 (t)	18.8	18.72				
	(s, 0.41) ^e				(s, 0.37)				
+ D_2 -CO-EtOD	68.30	21.8	30.27		18.33	19.3	3.31	1.71 (br	0.88
	(t, 0.44)		(s, 0.29)		(t, 0.44)		(br, 0.21)	spt, 0.44)	(d, ^b 5.0)
	68.22	21.8	30.18		18.22	19.3			
	(t, 0.56)		(s, 0.71)		(t, 0.56)				
	67.94 (qnt)	21.5	29.79 (t)	19.6					
	67.86 (qnt)	21.5	29.70 (t)	19.6					

^a Relative intensity, in parentheses, only quoted for β -shifted resonances. ^b Superimposed on a broader resonance to slightly higher field. ^c Not fully resolved. ^d Composite resonance of more than one compound. ^e Partial overlap of these signals makes integration approximate.

resonances due to C^3 being attached to C^2 with either H or D, we can directly determine the H:D ratio on C^2 as 0.44:0.56.

The C^1 resonance consists of two 1:1:1 triplets and two 1:2:3:2:1 quintets arising from CHD (triplets) and CD_2 (quintets) attached to C^2 with H or D. Once again the H:D ratio on C^2 can be calculated as 0.44:0.56, although, because of peak overlap, there is less precision on this calculation than on the measurement based on the C^3 resonance. There is no evidence for C^1H_2 being present. This would give a singlet resonance to low field of the low-field peak of the triplets. Analysis of the C^2 resonance then allows us to determine the CHD: CD_2 ratio on C^1 . The C^2 resonance appears as two singlets (from CH) and two 1:1:1 triplets (from CD). The singlets arise from C^2 experiencing three or four β shifts, *i.e.* from $(\text{CH}_2\text{D})_2\text{CHCHDOH/D}$ and from $(\text{CH}_2\text{D})_2\text{CHCD}_2\text{-OH/D}$. The CHD: CD_2 ratio on C^1 can then be assessed as 0.29:0.71.

With only four isotopomers present, it is then straightforward to estimate the amounts of each in the mixture if it is assumed that secondary isotope effects are negligible. These results are collected for this and other samples in Fig. 3.

Unfortunately, there are insufficient data available from this kind of spectral analysis for the analysis of more complex mixtures without making a number of assumptions, only some of which can readily be justified.

^{13}C - $\{^1\text{H}, ^2\text{D}\}$ NMR Spectra.—Analysis of 2-methylpropanol. Owing to the difficulties associated with the analysis of more complex mixtures of partially deuterated propanols using ^{13}C - $\{^1\text{H}\}$ NMR spectra (see above), we have used an alternative analytical method that has been employed by Brown and co-workers.^{9,10} This involves the measurement of ^{13}C resonances whilst decoupling both ^1H and ^2D . Measuring the spectra at the highest possible field (in our case at 151 MHz), it is then possible not only to see α and β shifts, but also γ shifts. In favourable cases, β shifts from different types of β -D can be resolved, as can γ shifts from different types of γ -D.

The 2-methylpropanol obtained from hydrocarbonylation of prop-2-en-1-ol using D_2 -CO in ethanol potentially consists of a mixture of the 18 different isotopomers shown in Fig. 2.

The resonance from C^2 attached to H, which is similar to that obtained in the ^{13}C - $\{^1\text{H}\}$ NMR spectrum measured at 75.4 MHz, is split into five signals corresponding to C atoms experiencing zero to four β shifts with decreasing δ values. Their relative intensities are 0.016:0.074:0.253*:0.434*:0.222 respectively. Assigning a' to the proportion of isomer A' (Fig. 3),

* These two resonances show further splitting, but this is not fully resolved.

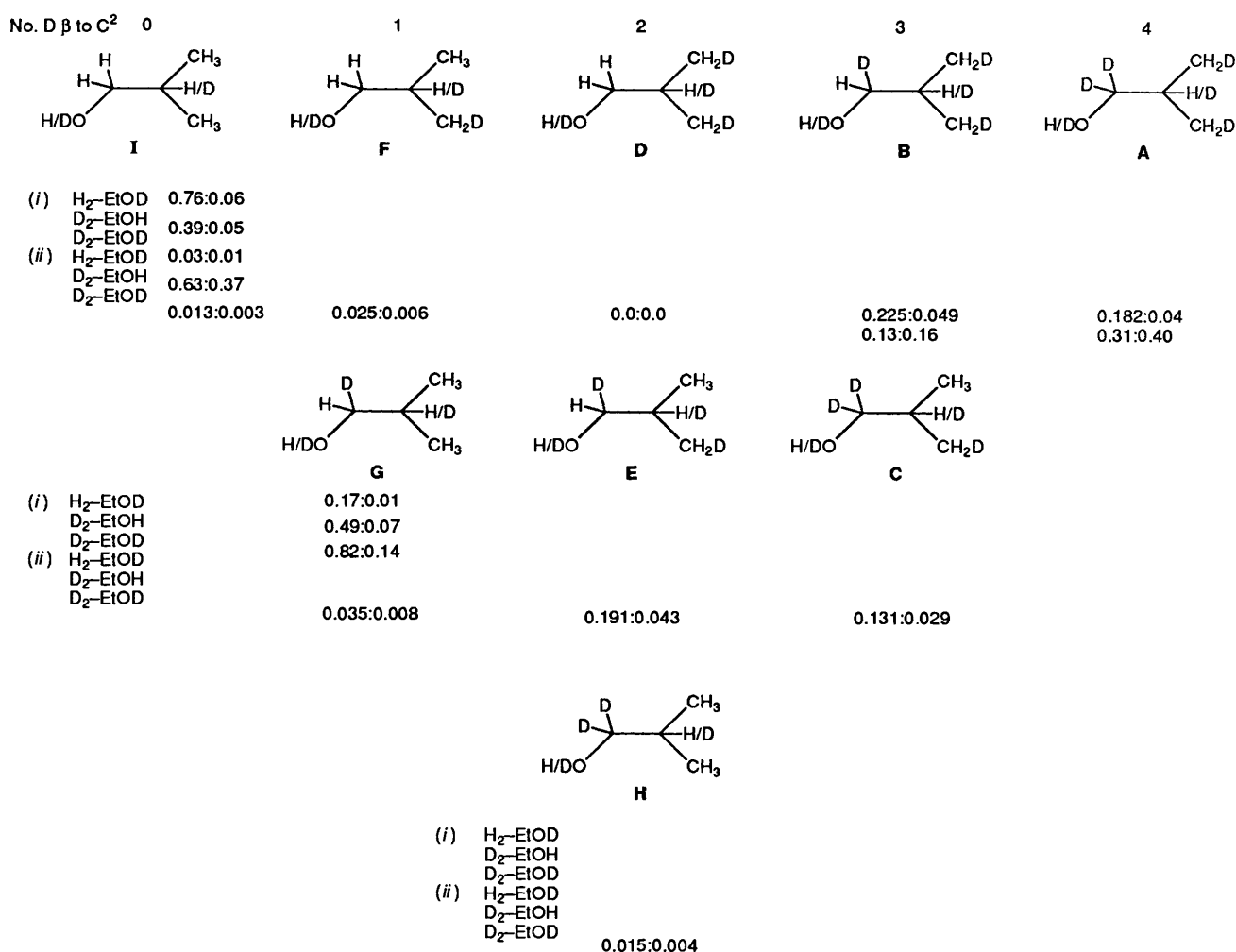


Fig. 2 Possible labelled products from catalytic reactions; A'-I' H on C², A''-I'' D on C². Numbers are presented as fractions of the total, e.g., a':a''. (i) 2-Methylpropanal; (ii) prop-2-en-1-ol

etc., it follows that $a' = 0.222$, $b' + c' = 0.434$, $d' + e' + h' = 0.253$, $f' + g' = 0.074$, $i' = 0.016$.

The resonance from C³H₃ shows very much better resolution in the ¹³C-¹H, ²D} NMR spectrum appearing as six singlets (Fig. 3) (in the ¹³C-¹H} spectrum at 75.5 MHz only a single peak is observed). The assignment of these resonances is aided by the analysis of a spectrum of a solution obtained from the hydrogenation of 2-methylpropanal using the same catalyst system with D₂ in EtOH. This contains 44% of I and 56% of G but the resonance from the C³H₃ groups appears as three peaks separated by 0.016 ppm, the two to lower frequency being of equal intensity. Three resonances arise because the methyl groups in G' are diastereotopic (since C¹ is a chiral centre) and hence inequivalent. It is also expected that the methyl groups of the two different diastereomers of E' will have different chemical shifts and will be shifted from the resonance of F' by a similar amount to that of E' from G'. This then allows the full assignment of the six singlets as follows in increasing order of chemical shift: C', E', H' + E', G' + F', G', I'. Assuming that the two diastereomers of E' are present in equal amounts, which is likely since the chiral centre on C¹ is believed to be formed by hydrogenation of the carbonyl group in 2-methylpropanal⁵ and there is unlikely to be a diastereoselectivity generated by the difference between CH₃ and CH₂D on C², remembering that I', G' and H' each contain two methyl groups and setting $f' + g' = 0.074$ as required by the C² resonance, it is then possible to calculate the relative proportions of the different isotopomers

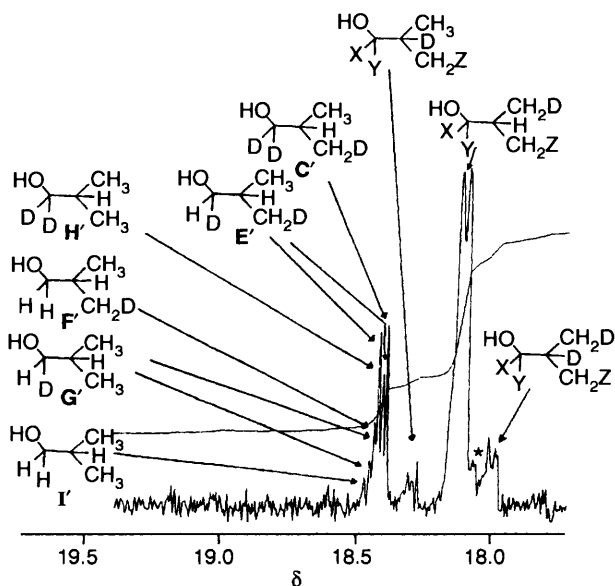


Fig. 3 The C³ resonance and assignments obtained in the ¹³C-¹H, ²D} NMR spectrum at 151 MHz of the fraction containing labelled 2-methylpropanol from hydrocarbonylation of prop-2-en-1-ol in EtOH using D₂-CO; X, Y and Z are H or D. The resonance marked with an asterisk is a ¹³C satellite of the CH₃ carbon of ethanol

as follows: $c' = 0.160$, $e' = 0.234$, $f' = 0.031$, $g' = 0.043$, $h' = 0.019$ and $i' = 0.016$.

Finally, with the assumption that the H:D ratio on C² is the same for all isotopomers (0.82:0.18, obtained from integration of the unshifted and β -shifted resonances of C³ or C¹), which seems to be valid since the shapes of β -shifted and non- β -shifted resonances on C³ and C¹ are the same, it is possible to compute the proportion of each of the 18 isotopomers in the complex mixture. These values are collected in Fig. 2.

In principle, it should be possible to carry out similar calculations based on the resonance from C¹, but in practice we find that the resolution of this resonance is not as good as that for the C³ atoms. We note, however, that since in this case A', B' and D' have two CH₂D groups, the relative intensity of the lines, reading from low frequency, should be 0.44:0.27:0.43:0.115:0.115:0.03.

Comparison with Other Possible Analytic Techniques.—For the simpler mixtures of isotopomers it is possible to carry out quantitative analysis using integration of the resonances in the ¹H NMR spectra provided that (a) each carbon atom bears no more than two different substitution patterns and that these are known (*i.e.* CH₂/CHD, CHD/CD₂ *etc.*) and (b) that at least one C atom bears only H atoms. For more complex systems, containing several different isotopomers, there are insufficient data in the ¹H NMR spectra to be able to obtain any reliable quantitative information. Similar problems occur for ²D NMR spectra although these can be useful for the analysis of *e.g.* complex mixtures of deuteriated toluenes.¹¹

Mass spectrometry can also be used for the analysis of complex mixtures of isotopomers, and indeed we have used it successfully for the quantitation of mixtures of un-, mono-, hepta- and octa-deuteriated propane.¹² However, different isotopomers which contain the same number of H and D atoms but in different positions cannot easily be quantitatively evaluated even from their fragments and there is the added complication of loss of H/D giving peaks which overlap with parent ions from other isotopomers.

Overall, the ¹³C NMR methods described in this paper are simpler and give more reliable data than any other available methods for the analysis of complicated mixtures of isotopomers.

Conclusion

We conclude that ¹³C NMR spectroscopy provides a powerful method for determining the exact quantitative distribution of deuterium labels in mixtures of multiple partially deuteriated products from catalytic reactions (in this case alcohols). For mixtures containing up to four different isotopomers the intensities of β -shifted resonances in ¹³C-¹H NMR spectra measured at medium field give sufficient information for a full analysis. For more complex systems this method does not provide enough information for the analysis without making certain assumptions, but a complete unambiguous analysis is possible using the analysis of β - and γ -shifted resonances in ¹³C-¹H, ²D NMR spectra measured at very high field.

Knowing the exact distribution of deuterium labels in these kinds of products provides detailed information which can be used to interpret the mechanistic features of the reactions in which they were formed. Preliminary conclusions based on these results have been published^{5,6} and more detailed analyses will be published separately.¹³

Experimental

Proton and ¹³C-¹H NMR spectra were recorded on a Bruker Associates WM 300 spectrometer, ¹³C-¹H, ²D spectra on a

Bruker Associates 600 spectrometer. Both instruments were operating in the Fourier-transform mode with noise proton decoupling or inverse gated proton decoupling. For the inverse gated decoupling the delay time between switching off the decoupling power and acquiring the data was 20 s.

Catalytic Reactions.—The catalyst precursor, either [RhH-(PEt₃)₃]¹⁴ (0.018 g) (heptene or heptanal as substrate) or [Rh₂(O₂CMe)₄]₂MeOH¹⁵ (0.01 g) and PEt₃ (0.059 cm³) (prop-2-en-1-ol or 2-methylpropanal as substrate) was dissolved in degassed ethanol or EtOD (4 cm³) under argon. To this was added the substrate (1 cm³). The resulting mixture was transferred anaerobically to a steel autoclave (250 cm³) fitted with a glass liner, which had previously been flushed three times with H₂-CO (1:1, 20 bar) and through which a steady stream of H₂-CO (1:1) was flowing. The autoclave was then pressurised to 40 bar with 1:1 H₂-CO and closed. It was placed in an oven at 120 °C for 4 h, removed, cooled in water, the pressure released and the oven opened. The products were separated by fractional distillation through a small vigreux column and examined by ¹H, ²D and ¹³C NMR spectroscopy.

For reactions using D₂ the autoclave was flushed three times with CO (20 bar). After releasing the pressure the autoclave was pressurised to 20 bar with D₂ followed by CO to make the pressure up to 40 bar.

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