

**NMR ISOTOPE SHIFTS AS A PROBE OF A RAPID NONDEGENERATE  
EQUILIBRIUM IN 2-ARYL-3-METHYL-2-BUTYL CATIONS**

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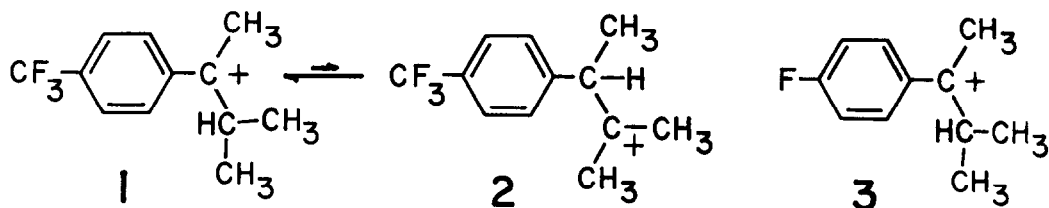
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**Abstract:** Equilibrium NMR isotope shifts can be detected for nondegenerate equilibria by comparison with intrinsic shifts in static model compounds. Such equilibrium shifts are smaller than in similar nondegenerate equilibria.

The NMR detection of isotopic perturbation of degenerate equilibria is a powerful method to study fast rearrangements. Changes in chemical shifts induced by isotopic substitution (NMR isotope shifts) have been particularly valuable in distinguishing between static  $\sigma$ -bridged carbocations and rapidly equilibrating classical cations.<sup>1</sup> In this paper, we demonstrate that NMR isotope shifts can also be used to detect nondegenerate rapid equilibria in carbocations. In a degenerate equilibrium, isotopic perturbation results in separate NMR signals for nuclei which are equivalent on a time-averaged basis in the unlabeled compound. However, equilibrium isotope shifts may be more difficult to detect in a nondegenerate equilibrium, because no time-averaged equivalence is created by the equilibrium, and because isotope shifts may be much smaller if the equilibrium constant differs substantially from unity. In nondegenerate cases, equilibrium isotope shifts of nuclei must be detected by comparison with intrinsic isotope shift behavior in nonequilibrating model compounds.<sup>2</sup>

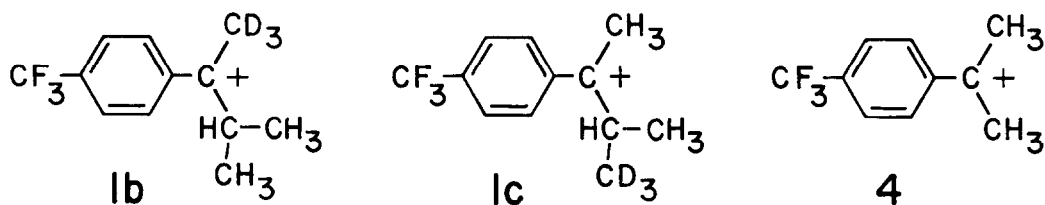
Appropriate aryl substitution in 2-aryl-3-methyl-2-butyl cations allows comparison between equilibrating and nonequilibrating structures. A hydride shift from the methine carbon (C<sub>3</sub>) of the isopropyl group in a 2-aryl-3-methyl-2-butyl cation, e.g. **1**, converts the ion from a 3° benzylic cation to a 3° alkyl cation, **2**. Brown and Periasamy recently demonstrated, via temperature dependence of <sup>13</sup>C NMR spectra of the carbocations in superacid media and the "tool of increasing electron demand," that the 3° alkyl form reaches a significant concentration in a rapid equilibrium when the aryl group is electron withdrawing, as in **1**.<sup>3</sup> Olah and coworkers had first suggested the occurrence of the hydride shift on the basis of line-shape changes in a <sup>1</sup>H NMR spectrum of **1**.<sup>4</sup> With electron donating aryl groups,

as in **3**, NMR spectra have the appearance expected for a static benzylic cation with no contribution from the hydride-shifted form.<sup>3</sup>



We prepared ions **1** and **3**, as the unlabeled ions and also with deuteriomethyl groups separately at each type of methyl position, by dissolving the appropriate alcohol precursors in  $\text{SbF}_5\text{-FSO}_3\text{H}/\text{SO}_2\text{ClF}$  at  $-78^\circ\text{C}$ . Our 15 MHz  $^{13}\text{C}$  spectra of the unlabeled cations are in good agreement with the earlier report.<sup>3,5</sup> The relevant chemical shifts for  $\text{C}_2$  (the carbenium center) and  $\text{C}_3$  are 274.5 and 51.6 ppm in **1** and 256.4 and 43.0 ppm in **3**. For another model ion, the 2-(4'-trifluoromethyl)phenyl-2-propyl cation, **4**, was similarly prepared, both unlabeled and with deuteriomethyl groups. The  $\text{C}^+$  chemical shift for **4** is 269.2 ppm.

The presence of the  $\mathbf{1} \rightleftharpoons \mathbf{2}$  equilibrium is indicated by the observation of a substantial isotope shift at both  $\text{C}_2$  and  $\text{C}_3$ , in both **1b** and **1c**.  $^{13}\text{C}$  signals are shown at right for  $\text{C}_3$ . The  $^{13}\text{C}$  spectrum at  $-80^\circ\text{C}$  of a mixture of the unlabeled ion, **1a**, with the labeled ions, **1b** and **1c**, shows that the  $\text{C}_2$  and  $\text{C}_3$  signals for **1a** are, within experimental error ( $\pm 0.2$  ppm), midway between the corresponding signals for the two labeled ions. Cation **1b** gives an isotope shift of +1.3 ppm (downfield) at  $\text{C}_2$  and -1.45 ppm (upfield) at the methine carbon. The isotope shifts for **1c** are in the opposite direction, -1.3 ppm at  $\text{C}_2$  and +1.45 ppm at  $\text{C}_3$ .



The direction of the isotope shifts for **1** are consistent with the NMR spectrum actually representing the weighted average spectrum of **1** in rapid equilibrium with a smaller amount of **2** (estimated<sup>3</sup> to be about 2% at  $-80^\circ$ ). Deuterium labeling at  $C_1$  (**1b**) perturbs the equilibrium toward **2**, so that  $C_2$  becomes shielded and  $C_3$  becomes deshielded. Labeling at the  $C_4$  methyl (**1c**) perturbs the equilibrium toward **1**, thereby deshielding  $C_2$  and shielding  $C_3$ .

The isotope shifts for **1** are clearly shown to be equilibrium isotope shifts by comparison of their magnitude to the magnitude of isotope shifts in **3** and **4**. Deuterium labeling in **3** produces no measurable isotope shifts at  $C_2$  or  $C_3$ . Rather, only a slight broadening of the  $C_2$  signal is observed when **3** is labeled at  $C_1$ , so that any isotope shift must be less than 0.2 ppm. Labeling of both methyl groups in the static model ion, **4**, causes only a small intrinsic isotope shift of +0.2 ppm at  $C^+$ . Per methyl group, this intrinsic shift is an order of magnitude smaller than the equilibrium isotope shifts observed for **1**.

The magnitude of isotope shifts is greater at  $C_3$  than  $C_2$  in **1** because the chemical shift difference between the isopropyl methine carbon (estimated  $\delta_C \approx 50$  ppm)<sup>3</sup> and a  $3^\circ$  alkyl cation center ( $\delta_C \approx 335$  ppm)<sup>6</sup> is greater than between a benzylic alkyl carbon ( $\delta_C \approx 70$  ppm)<sup>3</sup> and the  $3^\circ$  benzylic cation center ( $\delta_C \approx 279.3$  ppm)<sup>3</sup>. However, these equilibrium isotope shifts are much smaller than those observed for hydride shifts in degenerate equilibria<sup>7</sup> because of the small contribution of **2** to the equilibrium. In abstract terms, if an observed chemical shift,  $\delta$ , is the weighted average of two shifts  $\delta_A$  and  $\delta_B$ , i.e.,  $\delta = x\delta_A + (1-x)\delta_B$ , then the equilibrium isotope shift is given by equation (1)

$$\Delta\delta = \delta(D) - \delta(H) = (\delta_A - \delta_B)(x_D - x_H) \quad (1)$$

where  $x_D$  and  $x_H$  are the weighting factors for the deuterated and undeuterated compounds. Weighting factors are related to the equilibrium constants for  $A \rightleftharpoons B$  by  $K = (1-x)/x$ , so that equation (1) can be written in terms of equilibrium constants, as shown in equation (2):

$$\Delta\delta = (\delta_A - \delta_B) \frac{K_H/K_D - 1}{(K_H + 1)(1 + 1/K_D)} \quad (2)$$

This equation shows that for a given equilibrium isotope effect expressed as  $K_H/K_D$ , the value of the isotope shift,  $\Delta\delta$ , will tend to zero if  $K_H$  is very large or if  $K_D$  is very small. For example, when  $K_H/K_D = 1.5$  and  $\delta_A - \delta_B = 200$  ppm, the isotope shift will be 20 ppm for  $K_H = 1$  (i.e., a degenerate equilibrium) but only 1.9 ppm if  $K_H = 50$ .<sup>8</sup>

Our study with deuteriomethyl groups also reveals the presence of a rearrangement of 2-aryl-3-methyl-2-butyl cations that is slow on the NMR timescale at  $-80^{\circ}\text{C}$ . Starting with the alcohol precursor to **1b**, both ions **1b** and **1c** are found in solution. The analogous scrambling of labeled and unlabeled methyl groups occurs in **3**. The rearrangement is shown to take place in the cations by preparing **3-1-CD<sub>3</sub>** at about  $-110^{\circ}\text{C}$  and immediately measuring  $^{19}\text{F}$  spectra at  $-90^{\circ}$  which show a change in the ratio of **3-1-CD<sub>3</sub>** to **3-4-CD<sub>3</sub>** until equilibrium is reached. The rearrangements presumably take place by the hydride shift shown for **1**  $\rightleftharpoons$  **2**, then a methyl shift to give a  $2^{\circ}$  benzylic ion, and reversal of these steps with a different methyl. This process becomes fast on the NMR timescale at  $-30^{\circ}\text{C}$  and accounts for Olah's observation<sup>4</sup> of lineshape changes which average methyl groups in the  $^1\text{H}$  spectrum of **1** at  $-30^{\circ}$ .

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### References

- 1) For reviews of isotope shifts, see (a) P. E. Hansen, Ann. Rep. NMR Spectrosc., 15, 106 (1983); (b) D. A. Forsyth, Isot. Org. Chem., 6, 1 (1984).
- 2) NMR isotope shifts have been used previously to study nondegenerate tautomeric equilibria: (a) P. E. Hansen, F. Duus, and P. Schmitt, Org. Magn. Res., 18, 58 (1982); (b) A. Lycka and P. E. Hansen, Org. Magn. Res., 22, 569 (1984).
- 3) H. C. Brown and M. Periasamy, J. Am. Chem. Soc., 105, 529 (1983).
- 4) G. A. Olah, R. D. Porter, C. L. Jueell, and A. M. White, J. Am. Chem. Soc., 94, 2044 (1972).
- 5) Our chemical shifts relative to external  $\text{Me}_4\text{Si}$  (0.2 mm capillary) are consistently 0.7-0.9 ppm upfield of those in ref. 3.
- 6) G. A. Olah and D. J. Donovan, J. Am. Chem. Soc., 99, 5026 (1977).
- 7) (a) M. Saunders, L. Telkowski, and M. R. Kates, J. Am. Chem. Soc., 99, 8070 (1977); (b) H.-U. Siehl and H. Walter, J. Am. Chem. Soc., 106, 5355 (1984); (c) H.-U. Siehl and H. Walter, J. C. S. Chem. Commun., 77 (1985).
- 8) The  $K_{\text{H}}/K_{\text{D}}$  values for **1b** and **1c** in the **1** = **2** equilibrium are between 1.3 and 1.5. More precise values will be determined in a variable temperature study with a high-field NMR spectrometer.

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