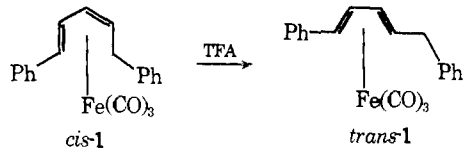
An Unusually Large Deuterium Isotope Effect in the Acid-Catalyzed Cis–Trans Isomerization of a Diene–Iron Tricarbonyl Complex

Sir:

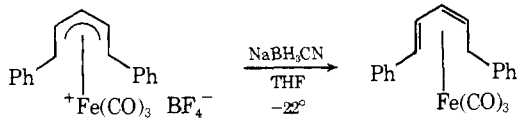
We wish to report that trifluoroacetic acid (TFA) catalyses the cis to trans isomerization of η^4-(1,5-diphenylpentadiene-1,3)tricarbonyliron (**1**), that the catalysis involves



cis-**1** *trans*-**1**

rate-determining protonation at the metal atom, and that this protonation occurs with an unusually large isotope effect of about 27.

Compound *cis*-**1** (mp 133–133.5°) is produced in about 30% yield by the cyanoborohydride reduction of the pentadienyl salt **2**.[1] It has been characterized by acceptable ele-

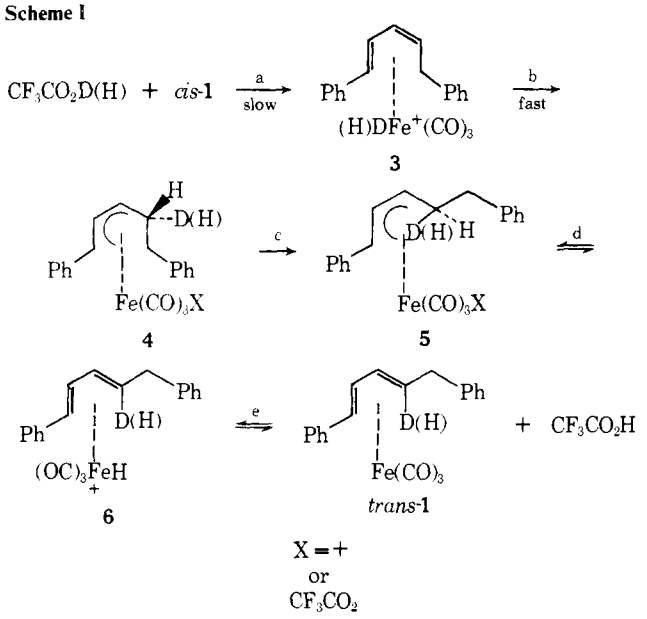


2 *cis*-**1**

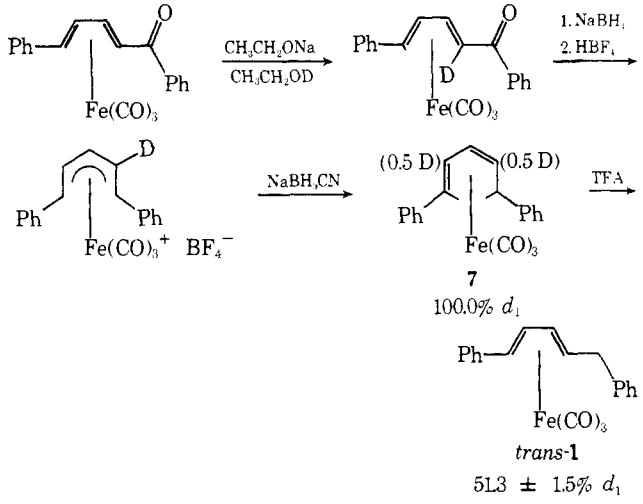
mental analysis and consistent ir, nmr, and mass spectral properties. In particular, the cis stereochemistry of the C_3–C_4 double bond is assigned on the basis of the method of synthesis, the observed rearrangement to *trans*-**1** on heating or on treatment with acid, and the small coupling constant between H_3 and H_4 (J_{34} = 6 Hz; the corresponding coupling in the trans species is 9 Hz).

Rearrangement of *cis*-**1 to** *trans*-**1** occurs rapidly on addition of an excess of TFA to a solution of the complex chloroform at 0°. Mixtures of TFA and TFA-d_1 resulted in the incorporation of varying amounts of deuterium into the product, all of which appeared to be at C_4 by nmr measurements. More accurate values for the extent of deuterium incorporation were obtained by mass spectral measurements on isolated *trans*-**1.** The values so obtained are shown in Table I. The amount of incorporation was independent of

Scheme I



Scheme II



whether the acid was added to the complex or the reverse. No d_2 or more highly deuterated species were observed even when the reaction time was substantially prolonged; likewise, *trans*-**1** incorporated only 1.7 ± 1.4% of one deuterium on stirring under identical conditions with 99.2% TFA-d_1.

A reasonable mechanism for this isomerization is shown in Scheme I. We have previously[2] shown that diene complexes exchange hydrogens in acid stereospecifically cis to the metal. The stereospecificity of the sequence in Scheme I was confirmed by subjecting compound **7**, synthesized as shown in Scheme II, to the isomerization conditions. The trans compound formed contained, as expected, half as much deuterium as starting **7.** This result, coupled with the slow rate of exchange of the trans species, indicates essentially stereospecific protonation–deprotonation of these diene complexes.

Further work in these laboratories[4] has demonstrated that the transfer of hydrogen from the metal to the ligand in closely related cases is rapid on the nmr time scale, while exchange of the metal hydride with external acid is slower.[5] Thus, reaction b is faster than reaction a. Furthermore, since *trans*-**1** does not incorporate deuterium, some reaction in the sequence must be essentially irreversible.[6] On steric grounds, we suggest that the irreversible step is reaction c.[7] The slow step in the sequence is therefore reaction a, i.e., protonation.

With this assumption, the isotope effect, k_H/k_D, on reaction a can be calculated from eq 1.[8] The values so obtained are shown in Table I.

$$\frac{k_H}{k_D} = \frac{T_H}{T_D}\left\{\frac{H_0}{D_0} + \frac{1}{2}\left[\frac{R\,\frac{H_0}{D_0} + 1}{\frac{T_H}{T_D} + 1}\right]\right\}^{-1} \qquad (1)$$

where T_H, T_D = amounts of d_0 and d_1 *trans*-**1** formed, H_0, D_0 = amounts of hydrogen and deuterium in starting acid, and R = ratio of moles *cis*-**1** to moles TFA (~0.01).

A final demonstration that the number obtained above represents a true kinetic isotope effect is the agreement of the observed *tritium* isotope effect with that predicted from the measured deuterium isotope effect, using the equation of Swain et al.[9] (eq 2).

$$k_H/k_T = (k_H/k_D)^r;\ 1.58 \geq r \geq 1.33 \qquad (2)$$

The tritium isotope effect was measured[10] by the amount of tritium incorporation into *trans*-**1** on carrying out the

Table I. Deuterium Incorporation into *trans*-1 and Calculated Isotope Effects

% D in TFA[a,e]	% D in *trans*-1[b]	k_H/k_D[c]
99.3 ± 0.3	71.5 ± 0.3	40 ± 13
92.7 ± 0.3	30.4 ± 0.3	27 ± 1
84.5 ± 0.3[f]	17.0 ± 0.3	27 ± 1
75.7 ± 0.3	10.4 ± 0.3	27 ± 1
59 ± 1[d]	6.1 ± 0.4	22 ± 2

[a] The deuterium content of the TFA was analyzed by addition of a known amount of chloroform and integration of the resonances due to acid and chloroform protons. [b] Obtained from measurement of at least four slow scans of the M − 3CO (*m/e* 276–277) peak; the molecular ion was very weak even at low voltages. The ratios of peak intensities in this cluster in undeuterated *trans*-1 were in accord with those calculated from known isotope abundances, demonstrating that hydrogen loss is not a source of error in these measurements. [c] See text. [d] This sample of acid contained approximately 20 mol % of water. [e] The mole ratio of acid to *cis*-1 was about 100. [f] Chloroform solution of complex added to acid (inverse addition).

isomerization under our standard conditions in labeled TFA (specific activity = (6.62 ± 0.02) × 10^{10} cpm/mol). The specific activity of carefully purified *trans*-1 was (6.36 ± 0.34) × 10^8 cpm/mol (average of two trials), whence k_H/k_T = 104 ± 6.

This value corresponds to a value of r = 1.41 ± 0.04 in eq 2, well within the expected range for a kinetic isotope effect.

The large magnitude of the isotope effect can be at least partially rationalized in terms of the proposed mechanism. The change in vibrational frequencies involved in the proton transfer between oxygen (ν_{OH} ~3600 cm^{-1}) and metal (ν_{MH} 1800–2000 cm^{-1}) is much larger than between oxygen and, say, carbon (ν_{CH} ~3000 cm^{-1}), and thus the ability to discriminate between hydrogen and deuterium in a transfer from oxygen to metal would be expected to be correspondingly greater. Therefore, the observation of a large isotope effect is consistent with the arguments above, and with the essential correctness of the mechanism in Scheme I.

Acknowledgment. This work was supported by grants from the National Science Foundation (GP 16358) and the Chevron Research Corporation.

Supplementary Material Available. Appendix I, the derivation of eq 1, will appear following these pages in the microfilm edition of this volume of the journal. Photocopies of the supplementary material from this paper only or microfiche (105 × 148 mm, 24× reduction, negatives) containing all of the supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D.C. 20036. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche, referring to code number JACS-75-907.

References and Notes

(1) The synthesis of this compound will be published later.
(2) T. H. Whitesides and R. W. Arhart, *J. Am. Chem. Soc.*, **93**, 5296 (1971).
(3) H. W. Whitlock, C. R. Reich, and R. L. Markezich, *J. Am. Chem. Soc.*, **92**, 6665 (1970).
(4) T. H. Whitesides and R. W. Arhart, accepted for publication, *Inorg. Chem.*
(5) Direct evidence for the relative rates of intra- and intermolecular exchange is obtained from examination of the NMR spectrum of cyclohexadiene iron tricarbonyl in TFA. Two sets of resonances are observed: one (~90%) due to unprotonated complex; the other (~10%) due to the *averaged* spectrum of the metal-protonated species. Similar results have been obtained by B. F. G. Johnson, J. Lewis, and D. Yarrow (*J. Chem. Soc., Chem. Commun.*, 235 (1972)) for (cyclohexadiene)(cyclopentadienyl)rhodium.
(6) If *trans*-1 isomerized back to *cis*-1 appreciably rapidly, deuterium would be incorporated into *trans*-1 by the reverse of Scheme I.
(7) Since the equilibrium concentration of *cis*-1 is very low,[7] the steric congestion in *cis*-1 must be large. This congestion is largely produced in the reverse of reaction c.
(8) This expression was derived by integrating the differential equations corresponding to

$$CF_3CO_2H + cis\text{-}1 \xrightarrow{k_H} trans\text{-}1\ (H)$$

$$CF_3CO_2D + cis\text{-}1 \xrightarrow{k_D} trans\text{-}1\ (D)$$

The second term results from the fact that in highly deuterated TFA the hydrogen concentration changes appreciably during the reaction even with a large excess of TFA. The correction introduced is negligible for <90% D_1 TFA, and eq 1 reduces to

$$\frac{k_H}{k_D} = \frac{T_H}{T_D}\frac{D_0}{H_0}$$

A detailed derivation will appear as an appendix in the microfilm edition of this journal.
(9) C. G. Swain, E. C. Stivers, J. F. Reuwer, Jr., and L. J. Schaad, *J. Am. Chem. Soc.*, **80**, 5885 (1958); see also, E. S. Lewis and J. K. Robinson, *ibid.*, **90**, 4337 (1968).
(10) We would like to thank Professor Howard Whitlock and Ms. Mary Dampier of this department for their assistance in performing this experiment.

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pH Dependence of the ^{13}C Spin–Lattice Relaxation Rate of the Carboxyl Carbon of Acetic Acid

Sir:

In a recent study of the pH dependence of the spin–lattice relaxation time (T_1) of the C2 proton of imidazole, it was concluded that paramagnetic metal ion impurities down to 10^{-7} *M* dominate the relaxation time in the neutral pH range.[1] This was concluded to be the origin of the minimum observed in the pH dependence of the T_1 value, since additions of Cu^{2+} ion at 10^{-6} to 10^{-4} *M* caused a more pronounced minimum, while the chelating agent EDTA reduced the effect.

In view of the relevance of such studies to biological molecules in aqueous solutions, and the extensive use of pulse techniques to measure ^{13}C relaxation times in peptides and proteins,[2-7] it was felt worthwhile to extend these studies to the observation of the ^{13}C resonance of a titrating functional group. The carboxyl group was chosen in view of the availability of highly enriched (90%) $CH_3{}^{13}COOH$ (Merck & Co., Rahway, N.J.). This reduced the time taken to measure the T_1 values by the spin inversion–recovery method,[1] so that only one sequence of pulses (d, π, τ, $\pi/2$) was generally required.

Acetic acid was one of the molecules studied in a consideration of the origins of ^{13}C relaxation phenomena in small molecules, in which it was concluded that for the carboxyl carbon atom the predominant relaxation mechanism was dipolar.[8] In a recent report, Armitage et al.[9] described a minimum in the pH dependence of the ^{13}C T_1 value of the carboxyl carbon atoms of various amino acids, which they attributed to a spin rotation mechanism.

In the present work ^{13}C relaxation times were measured at 55 MHz using a probe constructed at NIH and interfaced to the Varian HR 220 FT system. Pulse widths were typically 14 μsec for a 90° pulse, and delay times of the order of 50–250 sec (≃5 T_1) were used. Long T_1 values are especially sensitive to the absorption of oxygen from the air. To reduce this effect samples were transferred under a stream of nitrogen gas, and NMR tubes were filled with nitrogen before and after each pH measurement and were kept stoppered. Samples were 1 *M* $CH_3{}^{13}COOH$ in 0.1 *M* NaCl, and pH was adjusted with 1 *N* NaOH. Above the p*K* value (4.5) buffering capacity was minimal and it was difficult to obtain pH values in the range 5–11. The standard er-