4.11 (2 H, q, J = 7.0 Hz, CO_2CH_2), 5.25 (1 H, s, 13-H); ^{13}C NMR ($CDCl_3$) δ 13.9, 19.5, 28.4, 31.9, 40.4, 42.2, 49.4, 61.4, 66.0, 73.2, 100.7, 127.7, 150.8, 166.1, 171.3; mass spectrum m/z (relative intensity) 280 (M^+, 89), 206 (100). Anal. Calcd for $C_{15}H_{20}O_5$: C, 64.27; H, 7.19. Found: C, 64.09; H, 7.09.

Registry No. **4**, 136721-16-9; **5**, 136721-17-0; **6**, 136721-18-1; **7**, 136721-19-2; **8**, 136721-20-5; **9a**, 136721-21-6; **9b**, 136721-22-7; **10a**, 136721-23-8; **10b**, 136721-24-9; **11a**, 136721-25-0; **11b**, 136721-26-1; **12a**, 136721-27-2; **12b**, 136721-28-3; **14**, 136721-29-4; **15**, 136721-30-7; **16**, 136721-31-8; **19**, 136721-32-9; **20**, 136721-33-0; P, 675-10-5; $Br(CH_2)_3Br$, 109-64-8; $Br(CH_2)_5Br$, 111-24-0; (*E*)-$Br(CH_2)_3CH{=}CHCO_2Et$, 71032-10-5; $H_2C{=}CHCO_2H$, 79-10-7; $HO(CH_2)_2Cl$, 107-07-3; Ph_2CO, 119-61-9; 2-chloroethyl acrylate, 2206-89-5; 3-chloropropyl acrylate, 5888-79-9; ethyl (diethylphosphono)acetate, 867-13-0.

Anodic Oxidation of α-Substituted *p*-Xylenes. Electronic and Stereoelectronic Effects of α-Substituents in the Deprotonation of Alkylaromatic Radical Cations[1]

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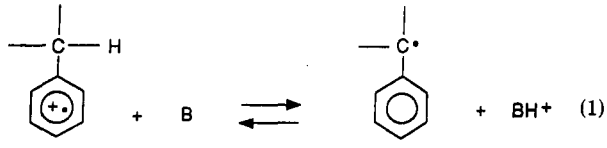
Received July 22, 1991

The effect of α-substituents on the deprotonation rate from the benzylic position of alkylaromatic radical cations, $k(CH_2Z)/k(CH_3)$, has been investigated by determining the intramolecular selectivity in the anodic oxidation in acetic acid of α-Z-substituted *p*-xylenes **1** (Z = H, OMe, OH, Me, *tert*-butyl, OAc, COOMe, CN), 5,6-dimethylindan **4** (R = H), and 2,2,5,6-tetramethylindan **4** (R = Me). Some oxidations induced by CAN have also been carried out. It has been found that, with the exception of when Z = *tert*-butyl, the deprotonation rate of $1^{\bullet+}$ is always faster from the CH_2Z group than from the CH_3 group, independently of the electron-donating or electron-withdrawing nature of Z. The electron-donating groups (OH, OMe, Me), however, exert a larger effect than the electron-withdrawing ones (COOMe, CN). The negligible deprotonation rate from CH_2-*t*-Bu has been ascribed to stereoelectronic effects (the bulky *tert*-butyl group does not allow the C–H bonds to be collinear with the π-system), the suggestion being nicely confirmed by the observation that the deprotonation rate from the position 1(3), relative to that from the 5(6)-methyl group, is almost identical in the radical cations of **4** (R = H and Me). The effect of the other α-substituents is mainly of electronic nature and has been rationalized on the basis of a variable transition-state structure for the deprotonation process. It is suggested that with +R groups most of the charge, in the transition state, has been transferred to the C_α–H bond where it can be stabilized by the α-substituent. With electron-withdrawing groups less charge transfer has taken place and the rate-enhancing effects of these groups is ascribed to their capability to significantly decrease the strength of the C_α–H bond.

Alkylaromatic radical cations are among the strongest carbon acids in solution (pK_a as negative as −30 or more in DMSO![3]) undergoing proton loss from an α-carbon, as shown in eq 1.



(1)

This process presents several aspects of theoretical and practical interest, and accordingly, it has been the object of intense investigations in the last decade. In particular, great attention has been given to the knowledge of the structural factors influencing the deprotonation rate and the position of the equilibrium.

By means of thermochemical cycles the pK_a values of a great number of alkylaromatic radical cations have been evaluated,[4] and today we have satisfactory information on the way these values are affected by the substrate structure. The factors which play the major role in this respect are the C_α–H bond energy and the oxidation potential of the parent substrate. In general, the thermodynamic acidity of an alkylaromatic radical cation decreases as the oxidation potential of the neutral substrate is lowered, i.e., by the presence of electron-donating ring substituents.

Information concerning structural effects on the kinetic acidity of alkylaromatic radical cations has come (directly) from laser photolysis[5] or pulse radiolysis[6] experiments as well as (indirectly) from kinetic[7] and intramolecular se-

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lectivity[8] studies of reactions involving radical cations as intermediates. At present, the available results indicate the following: (i) the deprotonation rate of an alkylaromatic radical cation can be very high, in some case not far from the diffusional limit; (ii) like the thermodynamic acidity, the kinetic acidity is decreased by electron-donating groups bonded to the ring. The effect on the rate is however much smaller than on pK_a, thus suggesting an early transition state for the deprotonation process; (iii) electron-donating groups make deprotonation faster when they are para than when they are meta to the acid center.

Another interesting suggestion is that the rate of proton loss from an alkylaromatic radical cation can be influenced by the relative orientation of the C_α–H bond and the aromatic π-system (stereoelectronic effects). The orientation most suited for cleavage would be that where the C_α–H bond and the aromatic π-system are collinear. If there is some steric hindrance to this alignment a substantial decrease in the rate of deprotonation is expected.

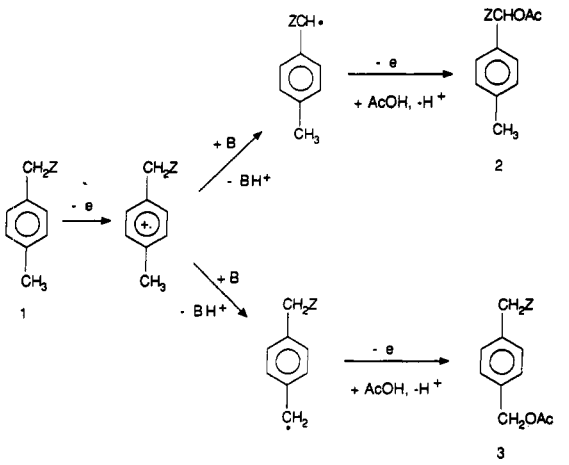
This idea was first put forward by Schulz and coworkers[9] almost two decades ago to rationalize the preferential oxidation of the methyl group with respect to the isopropyl group in the reaction of *p*-cymene with cobalt(III) acetate, a reaction thought (probably incorrectly, as shown by later work[8a,10]) to involve the intermediacy of a radical cation. Since then, further studies of a number of one-electron oxidation of *p*-cymene have produced controversial results and serious doubts have been raised on the actual role of stereoelectronic effects on that system,[11] even though the operation of these effects seems supported by calculations based on semiempirical methods.[12]

Only recently, convincing experimental evidence has been obtained indicating that stereoelectronic effects are very important in the deprotonation of 9-ethylanthracene radical cation,[13] where the alignment between the C_α–H bond and the π-system is made almost impossible by the steric interactions of the two peri hydrogen atoms with the α-methyl group. Negligible deprotonation from the C_α–H bond of the ethyl group was, accordingly, observed.

Clearly, the problem of stereoelectronic effects on the side-chain deprotonation reaction of aromatic radical cations is closely associated with that, more general, of the effects exerted by substituents directly bonded to the α-carbon of the alkyl group undergoing proton loss (α-substituents). Accordingly, these substituents can also influence the deprotonation rate by exerting "normal" electronic and steric effects which have, therefore, to be disentangled from the stereoelectronic ones.

Surprisingly enough, these effects have been given so far little attention in spite of the fact that information in this respect could help to clarify the role of stereoelectronic effects as well as provide us with a better insight on the transition-state structure of the deprotonation process.

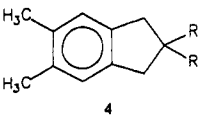
Scheme I



We have considered it worthwhile to address this problem, and to this purpose, an indirect approach has been used consisting in the study of the anodic oxidation of a number of α-Z-substituted *p*-xylenes **1** (Z = OMe, OH, Me, *t*-Bu, OAc, CO_2Me, CN) in acetic acid under conditions where the ECEC mechanism described in Scheme I is certainly operating.[14]

In view of the irreversibility of the deprotonation step, the relative reactivity of the substituted and the unsubstituted methyl group, $k(CH_2Z)/k(CH_3)$, in the deprotonation of $1^{\bullet+}$ can easily be determined by measuring the molar ratio of the two isomeric products (the benzylic acetates **2** and **3**). Certainly, the comparison of different Z groups requires that the effect of the nature of Z on the deprotonation rate from the *p*-CH_3 group is not very significant. Since Z in not directly bonded to the ring, we feel that, at least to a first approximation, this assumption is justified. In addition, it should also be considered that, dealing with relative reactivity data, the effects exerted by Z on the stability of the radical cation should influence the deprotonation rate from the CH_3 and the CH_2Z group in a substantially similar way.

To investigate the role of stereoelectronic effects we have also studied the indan derivatives **4** (R = H and Me). In these substrates the rate of deprotonation from the 5- and 6-methyl groups is compared with that from the benzylic positions 1 and 3 bearing substituents assimilable to an ethyl group, (**4** (R = H)) and to a *tert*-butyl group (**4** (R = Me)). However, due to the rigidity of the cyclopentane ring, the substituent cannot, in this case, significantly influence the orientation of the C_α–H bond with respect to the aromatic system, as it instead occurs for the Z groups in **1**.



4

In few cases oxidations induced by ceric ammonium nitrate (CAN) in acetic acid have been carried out. There is overwhelming evidence[15] that also these oxidations occur by the mechanism illustrated in Scheme I, leading to the same acetates **2** and **3** or to the corresponding nitrates. It seemed therefore of interest to compare the results of these

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(15) Reference 8a and references cited therein.

reactions with those of the anodic oxidations.

Results and Discussion

Anodic oxidations of 1 and 4 were carried out for the most part in AcOH/MeCN (3:1) at 25 °C, in an undivided cell (Pt electrodes, controlled potential) using Bu_4NBF_4 as the supporting electrolyte. The potential was between 1.7 and 2.3 V vs SCE and was always chosen in order to make the substrate the only electrochemically active species. To check the role of the experimental conditions few experiments were also run at constant current (5 mA/cm^2) and in one case the platinum anode was replaced by a graphite anode. In order to keep overoxidation to a minimum only 0.2–1 F/mol were left to pass through the solution.

CAN-promoted oxidations were performed in argon-deareated AcOH at 60 °C (they were too slow at lower temperatures) using an 1:1 substrate/CAN molar ratio, which, when the reaction stoichiometry is considered, means 2:1 excess of substrate.

At the end of the reaction, the mixtures were worked up as usual (see Experimental Section) and the reaction products were analyzed by GC, GC–MS, and NMR (comparison with authentic specimens). The current yields in the anodic oxidation ranged from 40 to 100%. The yields of products in the CAN-promoted reactions were around 30–40%.

In the oxidations of the xylenes 1 the expected benzylic acetates 2 and 3 were formed in all cases with the exception of the reactions of 1 (Z = OMe and OH), where *p*-methylbenzaldehyde, certainly deriving from decomposition of the α-acetoxy- and the α-hydroxybenzyl acetate, respectively, was the only product observed. With 1 (Z = *t*-Bu), the acetate 2 (Z = *t*-Bu) was formed in very small amounts in the anodic oxidation, but it was not detected in the CAN-promoted reaction. *p*-Methylbenzaldehyde was also observed in the anodic oxidation of 1 (Z = OAc) coming from some decomposition of 2 (Z = OAc), which was the main product together with 3 (Z = OAc).

The $k(CH_2Z)/k(CH_3)$ reactivity ratios in the deprotonation of $1^{\bullet+}$ were then evaluated from the relative yields of 2 and 3 or the aldehydes derived therefrom, determined by GC analysis, and statistically corrected. To check the internal consistency of the method the anodic oxidation of *p*-ethylbenzyl acetate was also studied, and from the relative yields of the two isomeric acetates obtained the $k(CH_2OAc)/k(CH_2CH_3)$ reactivity ratio was determined. When this ratio was combined with the $k(CH_2CH_3)/k(CH_3)$ ratio obtained from the oxidation of 1 (Z = CH_3), a value of $k(CH_2OAc)/k(CH_3)$ was found (1.3) which is in satisfactory agreement with that (1.6) obtained directly from the anodic oxidation of 1 (Z = OAc).[16]

The intramolecular reactivity ratios exhibited also little sensitivity to the electrolysis conditions (controlled potential vs constant current) as well as to the nature of the anode (platinum vs graphite) and to the amount of electricity passed (0.2 vs 1.0 F/mol) through the cell. All results are in Table I where for most substrates are also reported the *E*p values.

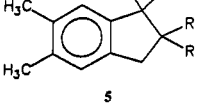
It can be noted that, where a comparison is possible, the relative reactivities determined by data of anodic and CAN-promoted oxidations follow the same trend. This observation indicates that in the electrochemical process the deprotonation of the radical cation should not be significantly influenced by absorption phenomena, a conclusion also supported by previous results[8a] as well as by the insensitivity of the reactivity ratios to the nature of the anode. The fact that the single figures are somewhat different is probably to be related to differences in the nature of the proton abstracting base under the two reaction conditions. Moreover, the reactions promoted by CAN have been carried out at a higher temperature than that used in the anodic oxidations and in a different solvent. Finally, as anticipated, there is no apparent trend between the stability of the intermediate radical cation, as expressed approximately by the *E*p value, and the relative reactivity values.

Table I. Relative Reactivity $k(CH_2Z)/k(CH_3)$ for the Deprotonation Reaction of α-Z-Substituted *p*-Xylene Radical Cations

Z	$k(CH_2Z)k(CH_3)$[a] anodic oxidation[c]	oxidation by CAN[d]	E_p[b] (V)
OH	>100[e]		2.39[f]
OCH_3	>100[g]	>100	
CH_3	14.1[h]	5.2[i]	2.16
CN	9.3		2.38
COOMe	3.4[l]		2.35
OAc	1.8[m]		2.45[f]
H	1	1	2.18
t-Bu	ca. 0.01[n]	<0.01[o]	2.13

[a] From the 2/3 product ratio obtained in the anodic or CAN-promoted oxidation reactions of *p*-xylenes 1. Average of at least two determinations. The error is ±10%. [b] vs SCE. Measured in MeCN at a platinum disk electrode at 100 mV/s. The average error is ±15 mV. [c] In AcOH/MeCN (3:1) at constant potential with Bu_4NBF_4 as the supporting electrolyte. Conversion 1 F/mol. [d] Oxidation in AcOH at 60 °C. [e] 3 (Z = OH) was not detected. [f] From Eberson, L.; Jonsson, L. *Acta Chem. Scand.* **1986**, *B40*, 79. [g] 3 (Z = OCH_3) was not detected. [h] 14.6 with conversion 0.2 F/mol. [i] From ref 8c. [l] 3.2 when the electrolysis has been run at constant current (5 mA/cm^2). [m] 1.3 at constant current (5 mA/cm^2) at 60 °C with graphite electrode as anode; 1.9 at constant current (5 mA/cm^2) at 60 °C with Pt electrodes. [n] This figure is subject to a great uncertainty since an extremely small amount of 2 (Z = *t*-Bu) was formed. [o] In this case 2 (Z = *t*-Bu) was not detected.

The products of the anodic oxidation of the indans 4 (R = H and Me) were the acetates 5 (R = H, Me) and 6 (R = H, Me). In the reaction of 4 (R = H) small amounts of 1,3-diacetoxy derivatives were also observed in the reaction product. The rate of proton loss from the substituted benzylic positions 1 and 3 of $4^{\bullet+}$ relative to that from the 5- and 6-methyl groups is given by the relative rate of formation of 5 and 6, $k5/k6$, and is determined by the molar ratio, statistically corrected, of the isomeric acetates 5 and 6. In the case of 4 (R = H) the moles of 5 also included those of the diacetate. The results were as follows: $k(5, R = H)/k(6, R = H) = 50$ and $k(5, R = Me)/k(6, R = Me) = 45$.



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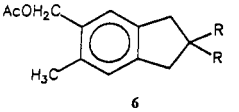

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To discuss the data of Table I, the first observation is that, with the exception of when Z is the *tert*-butyl group, deprotonation is always faster from CH_2Z than from CH_3. The negligible deprotonation rate from CH_2-*tert*-butyl is certainly due to steric effects since, on the contrary, when Z is Me, CH_2Z is much more reactive (about 14 times) than CH_3. Most probably, we are dealing with a stereoelectronic effect since simple molecular mechanics calculations as well

(16) However, a much smaller $k(CH_2OAc)/k(CH_3)$ ratio than that found by us can be evaluated by a previous study of the anodic oxidation of *p*-methylbenzyl acetate.[17] Apart from the fact that this oxidation was carried out on a much larger scale we are unable to find a reasonable explanation for this discrepancy.

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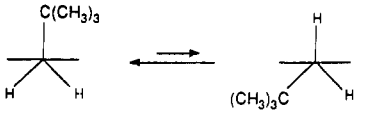
as molecular models indicate that the conformational equilibrium 7 ⇄ 8 is completely shifted toward the former conformation where the C–H bond is not collinear with the π-system. Conformation 8 is strongly disfavored by the steric interaction between the bulky *tert*-butyl group and the ring ortho hydrogens.



7 8

An unequivocal demonstration that this is actually the case is nicely provided by the observation that the dramatic difference between $k(CH_2CH_3)/k(CH_3)$ and $k(CH_2$-*t*-Bu$)/k(CH_3)$ (the former is 14, the second less than 0.01!) evinced by the study of the xylenes series, practically disappears as we move to the indane system. In fact, in the latter system the effect of an α-*tert*-butyl group, given by k(**5**, R = Me)/k(**6**, R = Me), is almost identical to that of an α-ethyl group, given by k(**5**, R = H)/k(**6**, R = H), which in turn is expected to be very close to the effect of an α-methyl group.[18]

Interestingly, whereas these data confirm that efficient deprotonation of an alkylaromatic radical cation requires collinearity between the C–H bond and the aromatic π-system, at the same time they also lead to the conclusion that steric hindrance to the approach of the base to the acid center is of little importance. This conclusion, clearly suggested by the results for the indane system, is in line with the early transition state proposed for these reactions.

Since stereoelectronic effects *always* operate in the direction of depressing the deprotonation rate, the observation that for all of the other Z substituents proton loss from CH_2Z is always faster than from CH_3 clearly indicates that electronic effects are also operating and that, in all cases, they outweigh the stereoelectronic ones.

A quite precise assessment of the contribution of stereoelectronic effects is possible for the methyl group by comparing the value (14) of the $k(CH_2CH_3)/k(CH_3)$ ratio evaluated from the oxidation of **1** (Z = Me) with the value (50) of the k(**5**, R = H)/k(**6**, R = H) ratio determined in the oxidation of **4** (R = H). It is reasonable to ascribe this difference to the stereoelectronic effect exerted by the α-methyl substituent in the deprotonation from the CH_2CH_3 group of $\mathbf{1}^{\bullet+}$ (Z = Me) and, if this interpretation is correct, the actual electronic effect of the α-methyl group should be 3–4 times stronger than the value resulting from the $k(CH_2CH_3)/k(CH_3)$ ratio reported in Table I.

The role of stereoelectronic effects for the other substituents is expected to be less important, or of comparable magnitude, with respect to that of the methyl group since, with the possible exception of CO_2Me, all the substituents displayed in Table I are less space demanding than CH_3.[19,20] Thus, even though the stereoelectronic effects can somewhat contribute to the observed reactivity ratios, the conclusion that both electron-donating and electron-withdrawing α-substituents increase the deprotonation rate and that the rate-enhancing effect is much larger for +R groups, like OH, OMe, and to a lesser extent Me, than for –R groups like CO_2Me and CN, is certainly possible.

To rationalize the stereoelectronic and electronic effects discussed above it might simply be suggested that the stabilization of the incipient benzylic radical plays an important role in the transition state of the deprotonation process. Accordingly, such a stabilization is expected to be enhanced by the collinearity of the C_α–H bond and the π-system, and moreover, it is known that a carbon-centered radical is stabilized by both electron-donating and electron-withdrawing substituents.

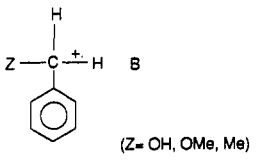
However, we attribute only a secondary importance to this factor for the following two reasons. First, as already mentioned, there is evidence for an early transition state in the deprotonation reactions of alkylaromatic radical cations. Therefore, the structure of the transition state should resemble that of the radical cation much more than that of the benzyl radical. Second, the +R groups OH and OMe exhibit a rate-enhancing effect significantly larger than that of the –R groups CN and CO_2Me, in spite of the fact that the latter are much more effective than the former in stabilizing a carbon radical.[21]

We feel that a more plausible explanation of our results may be provided by the suggestion that, by analogy with observations concerning the behaviors of radical anions,[22] the cleavage of the C_α–H bond in an alkylaromatic radical cation requires an intramolecular electron transfer from the σ-orbital of the C–H bond to the SOMO orbital of the aromatic system.

This view, which has also been considered in dealing with the very close problem of the breaking of the C_α–C bond in alkylaromatic radical cations,[23,24] nicely accounts for the observed stereoelectronic effects since the intramolecular electron transfer certainly needs the coplanarity of the orbitals involved and therefore of the C–H bond and the π-system.

The rationalization of the electronic effects of the α-substituents is less straightforward, but it too becomes possible if the additional assumption is made that in the transition state of the deprotonation process, the extent of the intramolecular electron transfer may be variable, depending on the nature of the α-substituent itself.

When Z is an electron-donating +R group (OH, OMe, and Me), electron transfer from the C–H bond to the π-system, in the transition state might have progressed to a much larger extent than the transfer of the proton to the base, and a consistent fraction of the positive charge might therefore reside on the C–H bond where it can be stabilized by the electron-donating group (structure **9**).



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In contrast, with electron-withdrawing substituents which cannot stabilize a positive charge, electron transfer may somewhat lag behind C–H bond scission and the rate-enhancing effects of these groups might be due to their capability to significantly decrease the strength of the

(18) Steric and electronic effects of the methyl and the ethyl groups are very similar, as shown by the almost identical values of σ and E_s for the two groups.[19]

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adjacent C–H bond by an inductive effect. In this respect, it is of interest to note that α-cyanotoluene radical cation is a much stronger acid than toluene radical cation, a substantial part of this difference being due to the fact that the benzylic C–H bond is 6 kcal/mol weaker in α-cyanotoluene than in toluene.[3] Of course, in view of the reactant-like structure of the transition state the kinetic effect cannot be that large and it is reasonable that electron-withdrawing Z groups influence the deprotonation rate to a much less extent than +R groups, like OH and OMe, which can delocalize a positive charge, as described before.

Of course, even though the possibility that structural modifications in the substrate significantly modify the transition-state structure of a reaction is not certainly a rare phenomenon,[25] this explanation has to be considered only tentative and further work, possibly also of theoretical nature, is certainly needed.

Conclusions

The present work has clearly shown that the deprotonation rate of alkylaromatic radical cations is profoundly influenced by substituents on the α-carbon of the acidic alkyl group (α-substituents), which exert both steric and electronic effects.

α-Substituents of large steric requirements, like the *tert*-butyl group, strongly depress the deprotonation rate, and it has unequivocally been demonstrated that the phenomenon is due to the capacity of the substituent to hinder the collinearity between the C_α–H bond and the aromatic π-system (stereoelectronic effect). Steric hindrance to the approach of the base appears of negligible importance.

With the other substituents (OH, OMe, OAc, CN, COOMe) the role of electronic effects outweighs that of the stereoelectronic ones, as indicated by the observation that *all* groups increase the deprotonation rate with respect to that of the unsubstituted CH_3 group, the rate enhancing effect being much larger with electron-donor +R substituents, expecially OH and OMe, than with electron-withdrawing –I and –R substituents (CN, COOMe).

Both stereoelectronic and electronic effects may be rationalized by suggesting that an intramolecular electron transfer from the σ-orbital of the C_α–H bond to the aromatic π-system is necessary in order for deprotonation to take place. This hypothesis certainly explains the collinearity requirement of the C–H bond and the π-system, and moreover it can also account for the observed electronic effects if the additional assumption is made that in the transition state of the deprotonation process the intramolecular electron transfer occurs to a variable extent depending on the nature of the α-substituent. With +R groups electron transfer has extensively progressed so that in the transition state most of the positive charge resides on the C_α–H bond where it can be stabilized by the α-substituent. In contrast, with –I and –R groups electron transfer has progressed to a little extent and the α-substituents may increase the deprotonation rate thanks to their ability to weaken the C_α–H bond by an inductive effect.

Experimental Section

^{1}H NMR spectra were recorded at 80 MHz on a Bruker WP 80 or, when specified, at 200 MHz on a Bruker AC 200 spectrometer in $CDCl_3$ solution and in the presence of tetramethylsilane as an internal standard. *J* values are given in Hz. GC–MS analyses were performed at 70 eV on a HP 5890 gas chromatograph equipped with 12 m × 0.2 mm methylsilicone gum capillary column and coupled with an HP 5970 MSD spectrometer. GC analyses were performed on a Varian 3400 gas chromatograph equipped with 25 m × 0.2 mm methylsilicone gum capillary column. Elemental analyses were performed on a Carlo Erba M 1106 elemental analyzer. Melting points were determined with a Buki M 510 instrument and were uncorrected.

Starting Materials. Ceric ammonium nitrate (Merck, 99% pure) was dried by heating at 85 °C for 1 h. *N*-Bromosuccinimide (Erba) was recrystallized from water. 2,2′-Azobis(isobutyronitrile) (Merk) was used as received. Acetic acid (Erba RP) was thoroughly purged with pure argon before use. α,α′-Dibromo-*p*-xylene, *p*-methylbenzaldehyde, ***p*-ethyltoluene** (1, Z = Me), ***p*-methylbenzyl alcohol** (1 Z = OH), and *p*-ethylbenzyl alcohol, of the highest grade of purity (Aldrich) were used as received. **4-Methylbenzyl cyanide** (1, Z = CN) (Aldrich) was fractionally distilled before use. ***p*-Methylbenzyl acetate** (1, Z = OAc) was prepared from *p*-methylbenzyl alcohol by direct esterification with acetic anhydride. **Methyl *p*-tolylacetate** (1, Z = COOMe) was prepared by acid-catalyzed esterification of *p*-tolylacetic acid in refluxing methanol. ***p*-Methylbenzyl methyl ether** (1, Z = OMe) was prepared in 78% yield by deprotonation of *p*-methylbenzyl alcohol with sodium hydride in DMSO and successive alkylation with methyl iodide. ***p*-Methylneopentylbenzene** (1, Z = *t*-Bu) was prepared as reported in the literature.[26] **5,6-Dimethylindan** (4, R = H) was prepared as follows. To 3.5 g (20 mmol) of 5,6-dimethylindan-1,3-dione[27] in diethylene glycol (20 mL) were added 99% hydrazine hydrate (4 mL) and potassium hydroxide (6.4 g, 0.11 mmol), and the mixture was heated at 80 °C until most of the potassium hydroxide was dissolved and then refluxed 1.5 h. The condenser was replaced by a 20-cm Vigreux column, and the brown liquor was distilled until the temperature reached 200 °C and ca. 10 mL of a two phases mixture were collected. Petroleum ether (5 mL) was added to the distillate, the organic phase was separated, and the aqueous phase was extracted with petroleum ether (3 × 5 mL). The collected organic phases were dried with sodium sulfate, and the solvent was evaporated at reduced pressure by keeping the bath temperature below 30 °C. The residue was finally chromatographed on silica gel (petroleum ether as the eluent) to recover 1.6 g (54%) of 4 (R = H) more than 99% pure by GLC: ^{1}H NMR (200 MHz) δ 7.01 (s, 2 H), 2.84 (t, *J* = 7.3, 4 H), 2.22 (s, 6 H), 2.05 (p, *J* = 7.3, 2 H); MS *m/z* 146 (M^+, 31), 131 (100), 115 (19), 105 (4), 91 (16), 77 (8), 63 (7), 51 (12). Anal. Calcd for $C_{11}H_{14}$ (146.23): C, 90.35; H, 9.65. Found: C, 90.12; H, 9.71. **2,2,5,6-Tetramethylindan (4, R = Me).** Sodium (3.2 g, 0.14 mol) was dissolved in anhydrous ethanol (100 mL), and 5,6-dimethylindan-1,3-dione (12.0 g, 69 mmol) and methyl iodide (15 mL, 34 g, 0.24 mol) were added. The mixture was refluxed 4 h and, after cooling at room temperature, was poured into water (500 mL) and extracted with chloroform (3 × 100 mL), and the collected organic extracts were dried with sodium sulfate. After solvent evaporation the resulting brown oil was chromatographed on silica gel by eluting with a 8:2 petroleum ether/diethyl ether mixture to isolate 6.7 g of 2,2,5,6-tetramethylindan-1,3-dione [^{1}H NMR δ 7.73 (s, 2 H), 2.46 (s, 6 H), 1.28 (s, 6 H)]. 2,2,5,6-Tetramethylindan-1,3-dione (6.5 g, 32 mmol) was refluxed 30 min with amalgamated zinc dust in 20% aqueous hydrochloric acid (100 mL). After being cooled at 20 °C, the mixture was poured into water (100 mL) and extracted with petroleum ether (3 × 100 mL). The collected organic phases were washed with water and dried with sodium sulfate, and the solvent was evaporated at reduced pressure. The GC–MS analysis of the crude product showed the presence of a main product at M^+ 174 together with four minor products at M^+ 176 (probably dihydroindan isomers coming from a partial reduction of the aromatic ring in addition to the carbonyl groups). These minor products disappeared when the crude mixture was heated at 180–190 °C for 30 min in the presence of palladium (10%) on activated carbon (200 mg) whilst air was cautiously bubbled in. Chromatography of the crude product on silica gel by eluting with

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petroleum ether allowed us to isolate 4 (R = Me) as white crystals: mp 42–42.5 °C; ^{1}H NMR δ 6.93 (s, 2 H), 2.67 (s, 4 H), 2.22 (s, 6 H), 1.13 (s, 6 H); MS (70 eV) m/z 174 (M^+, 38), 159 (100), 144 (16), 128 (20), 115 (14), 91 (10), 77 (8). Anal. Calcd for $C_{13}H_{18}$ (174.29): C, 89.59; H, 10.41. Found: C, 89.25; H, 10.61.

Structure Determination of the Reaction Products. The following products of the anodic and CAN-promoted oxidation of 1 and 4 were identified by comparison of their ^{1}H NMR and MS spectra and GC retention times with those of authentic specimens prepared as follows. ***p*-Ethylbenzyl acetate** (3, Z = Me) was obtained from *p*-ethylbenzyl alcohol by direct esterification with acetic anhydride. **1,4-Bis(acetoxymethyl)benzene** (3, Z = OAc) was prepared by acetolysis of α,α′-dibromo-*p*-xylene. **Methyl [4-(acetoxymethyl)phenyl]acetate** (3, Z = COOMe) and **methyl α-acetoxy-*p*-tolylacetate** (2, Z = COOMe) were prepared as follows. Methyl *p*-tolylacetate (1.02 g, 6.2 mmol) and NBS (1.10 g, 6.2 mmol) in anhydrous CCl_4 (30 mL) were refluxed 3 h under nitrogen after addition of azobisisobutyronitrile (0.1 g). The cooled mixture was filtered and the solvent was evaporated at reduced pressure. The residue was dissolved in acetic acid (40 mL) and refluxed 15 h in the presence of potassium acetate (7.7 g, 79 mmol). The mixture was diluted with water (200 mL) and extracted with diethyl ether (3 × 20 mL). The collected organic phases were washed with 5% aqueous $NaHCO_3$ then with water and dried with Na_2SO_4. After solvent evaporation, chromatography of the residue on silica gel (9:1 petroleum ether/diethyl ether mixture as the eluent) allowed to isolate first 2 (Z = COOMe) (54 mg): ^{1}H NMR δ 7.45–7.10 (m, 4 H), 5.92 (s, 1 H), 3.73 (s, 3 H), 2.37 (s, 3 H), 2.18 (s, 3 H); MS m/z 222 (M^+, 8), 190 (17), 180 (10), 163 (10), 121 (100), 91 (25), 73 (13), 43 (83). Anal. Calcd for $C_{12}H_{14}O_4$ (222.24): C, 64.85; H, 6.35. Found: C, 65.07; H, 6.41. To the second eluted product the structure of 3 (Z = COOMe) (300 mg) was assigned on the basis of the following spectral and analytical data: ^{1}H NMR δ 7.30 (s, 4 H), 5.09 (s, 2 H), 3.70 (s, 3 H), 3.62 (s, 2 H), 2.10 (s, 3 H); MS m/z 222 (M^+, 17), 180 (28), 163 (17), 135 (5), 120 (31), 91 (34), 77 (16), 43 (100). Anal. Calcd for $C_{12}H_{14}O_4$ (222.24): C, 64.85; H, 6.35: Found: C, 64.77; H, 6.06. **α-Cyano-4-methylbenzyl acetate** (2, Z = CN) was prepared in 91% yield by direct esterification of α-hydroxy-*p*-tolylacetonitrile, the latter obtained by standard procedure for cyanohydrin synthesis:[28] ^{1}H NMR δ 7.47–7.25 (m, 4 H), 6.40 (s, 1 H), 2.41 (s, 3 H), 2.17 (s, 3 H); MS m/z 189 (M^+, 29), 147 (62), 129 (88), 103 (29), 91 (23), 77 (29), 43 (100). Anal. Calcd for $C_{11}H_{11}NO_2$ (189.21): C, 69.83; H, 5.86; N, 7.40. Found: C, 69.64; H, 6.31; N, 7.37. **4-(Cyanomethyl)benzyl acetate** (3, Z = CN) was prepared with the same procedure described for 3 (Z = COOMe) except that only 3 (Z = CN) was recovered by column chromatography of the crude product: ^{1}H NMR δ 7.36 (s, 4 H), 5.11 (s, 2 H), 3.76 (s, 2 H), 2.11 (s, 3 H); MS m/z 189 (M^+, 9), 162 (13), 147 (26), 130 (30), 107 (57), 91 (17), 77 (15), 43 (100). Anal. Calcd for $C_{11}H_{11}NO_2$ (189.21): C, 69.83; H, 5.86; N, 7.40. Found: C, 70.02; H, 5.89; N, 7.71. **4-Methylbenzylidene diacetate** (2, Z = OAc) was prepared as described in the literature.[29] 2 (Z = OAc): mp 81–81.5 °C; ^{1}H NMR δ 7.67 (s, 1 H), 7.55–7.15 (m, 4 H), 2.39 (s, 3 H), 2.13 (s, 6 H); MS m/z 222 (M^+, 2), 179 (9), 163 (4), 119 (100), 91 (35), 65 (15), 43 (96). Anal. Calcd for $C_{12}H_{14}O_4$ (222.24): C, 64.85; H, 6.35. Found: C, 64.52; H, 6.30. ***α-tert*-Butyl-*p*-methylbenzyl acetate** (2, Z = *t*-Bu) was prepared in 71% yield by reduction of *tert*-butyl *p*-tolyl ketone with $LiAlH_4$ and successive esterification of the resulting *tert*-butyl *p*-tolyl carbinol with acetic anhydride: mp 52.5–53 °; ^{1}H NMR δ 7.35–7.10 (m, 4 H), 5.58 (s, 1 H), 2.38 (s, 3 H), 2.12 (s, 3 H), 1.09 (s, 9 H); MS m/z 220 (M^+, 8), 163 (29), 145 (4), 121 (100), 91 (17), 77 (8), 43 (46). Anal. Calcd for $C_{14}H_{20}O_2$ (220.31): C, 76.33; H, 9.15. Found: C, 76.03; H, 9.07. **5-(Acetoxymethyl)-6-methylindan** (6, R = H) was prepared as follows. 5-Methylindan-1,3-dione[27] (4.0 g, 25 mmol) was reduced exactly as described in the synthesis of 4 (R = H) to give pure 5-methylindan (1.7 g, 51%) as a colorless liquid: ^{1}H NMR δ 7.0 (m, 3 H), 2.87 (br t, J = 6.8, 4 H), 2.31 (s, 3 H), 2.03 (sym m, 2 H); MS m/z 132 (M^+, 34), 117 (100), 91 (18), 77 (11), 65 (11), 51 (16). To 5-methylindan (1.5 g, 11 mmol) in 85% aqueous acetic acid (20 mL) was added bromine (1.8 g, 11 mmol) dropwise at 20 °C in the dark. The mixture was left to react for 1 h while being stirred, then was poured into 0.1 N aqueous sodium thiosulfate (100 mL) and extracted with diethyl ether (3 × 25 mL). The collected organic phases were dried with sodium sulfate, and the solvent was evaporated to give a crude product (2.0 g) whose ^{1}H NMR and GC–MS data were consistent with a 3:1 mixture of 5-bromo-6-methylindan and 4-bromo-5-methylindan. 5-Bromo-6-methylindan: ^{1}H NMR δ 7.38 (s, 1 H), 7.09 (s, 1 H), 2.8 (m, 4 H), 2.36 (s, 3 H), 2.05 (sym m, 2 H); MS m/z 212 (M + 1, 26), 210 (M − 1, 27), 131 (100), 116 (32), 115 (34), 91 (29), 77 (14), 51 (27). 4-Bromo-5-methylindan: ^{1}H NMR δ 7.0 (m, 2 H), 2.9 (m, 4 H), 2.38 (s, 3 H), 2.1 (m, 2 H); MS m/z 212 (M + 1, 29), 210 (M − 1, 31), 131 (100), 116 (31), 91 (22), 64 (19), 51 (18). The above mixture (1.7 g, 8.0 mmol) in diethyl ether (5 mL) was left to react for 8 h with magnesium chips (200 mg, 8 mmol) under reflux. Paraformaldehyde (0.5 g, 17 mmol) was added, and the mixture was refluxed again overnight. The resulting brown suspension was poured into 5% aqueous sulfuric acid (50 mL) and extracted with diethyl ether (3 × 100 mL). The collected organic phases were dried with sodium sulfate, and the solvent was evaporated at reduced pressure. The resulting brown oil was dissolved in dichloromethane (3 mL), triethylamine (0.50 g, 5 mmol), acetic anhydride (0.50 g, 5 mmol), and 4-pyrrolidinopyridine (50 mg, 0.3 mmol) were added, and the mixture was allowed to react 15 min at 20 °C. After solvent evaporation, chromatography of the crude product on silica gel (9:1 petroleum ether/diethyl ether mixture as the eluent) recovered 120 mg of pure 6 (R = H) together with 200 mg of a 1.5:1 mixture of 6 (R = H) and 4-(acetoxymethyl)-5-methylindan. 6 (R = H): ^{1}H NMR (200 MHz) δ 7.19 (s, 1 H), 7.08 (s, 1 H), 5.09 (s, 2 H), 2.88 (broad t, J = 7.4, 4 H), 2.32 (s, 3 H), 2.08 (s, 3 H), 2.05 (sym m, 2 H); MS m/z 204 (M^+, 3), 145 (33), 129 (39), 115 (22), 91 (15), 77 (9), 43 (34). Anal. Calcd for $C_{13}H_{16}O_2$ (204.27): C, 77.44; H, 7.89. Found: C, 77.28, H, 8.05. An identical procedure was used to synthetize **5-(acetoxymethyl)-2,2,6-trimethylindan** (6, R = Me) starting from 2,2,5-trimethylindan, the latter prepared by Clemmensen reduction of 2,2,5-trimethylindan-1,3-dione[26] as described for 4 (R = Me). **6 (R = Me)**: ^{1}H NMR (200 MHz) δ 7.12 (s, 1 H), 7.01 (s, 1 H), 5.08 (s, 2 H), 2.68 (s, 4 H), 2.30 (s, 3 H), 2.09 (s, 3 H), 1.14 (s, 6 H); MS m/z 232 (M^+, 3), 190 (1), 172 (100), 157 (34), 91 (13), 43 (77). Anal. Calcd for $C_{15}H_{20}O_2$: C, 77.55; H, 8.68. Found: C, 77.73; H, 8.82.

The following products were isolated by chromatography on silica gel of the crude mixture from the anodic oxidation of 1 (Z = *t*-Bu, Me) and 4 (R = H, Me). ***p*-(2,2-Dimethylpropyl)benzyl acetate (3, Z = *t*-Bu)**: ^{1}H NMR δ 7.30–7.10 (m, 4 H), 5.10 (s, 2 H), 2.50 (s, 2 H), 2.11 (s, 3 H), 0.91 (s, 9 H); MS m/z 220 (M^+, 8), 163 (4), 145 (6), 122 (13), 104 (100), 57 (52), 43 (39). Anal. Calcd for $C_{14}H_{20}O_2$ (220.31): C, 76.33; H, 9.15. Found: C, 75.98; H, 9.12. **α-Methyl-*p*-methylbenzyl acetate (2, Z = Me)**: ^{1}H NMR δ 7.30–7.03 (m, 4 H), 5.82 (q, J = 6.7, 1 H), 2.30 (s, 3 H), 2.02 (s, 3 H), 1.48 (d, J = 6.7, 3 H); MS m/z 178 (M^+, 24), 136 (39), 117 (78), 91 (46), 65 (24), 43 (100). Anal. Calcd for $C_{11}H_{14}O_2$ (178.23): C, 74.13; H, 7.92. Found: C, 73.95; H, 7.78. **1-Acetoxy-5,6-dimethylindan (5, R = H)**: ^{1}H NMR δ 7.19 (s, 1 H), 7.06 (s, 1 H), 6.22–6.08 (four peaks, 1 H), 3.2–2.7 (m, 2 H), 2.7–1.9 (m, 2 H), 2.27 (s, 6 H), 2.07 (s, 3 H); MS m/z 204 (M^+, 0.5), 161 (4), 145 (43) 144 (100), 129 (68), 115 (16), 91 (11), 77 (7), 43 (22). Anal. Calcd for $C_{13}H_{16}O_2$ (204.27): C, 77.44; H, 7.89. Found: C, 77.61; H, 8.12. From the crude product of the anodic oxidation of 4 (R = H) a mixture of ***cis*- and *trans*-1,3-diacetoxy-5,6-dimethylindan** was also isolated as a minor component: ^{1}H NMR referred to the main isomer, δ 7.21 (br s, 2 H), 6.38–6.24 (three peaks, 2 H), 2.50 (sym m, 2 H), 2.28 (s, 6 H), 2.08 (s, 6 H); MS m/z 203 (M^+ − CH_3COO, 1.6), 202 (10), 160 (100), 145 (21), 128 (11), 91 (7), 43 (36); referred to the minor isomer, δ 7.21 (br s 2 H), 6.13–5.99 (four peaks, 2 H), 3.2–2.8 (m, 2 H), 2.28 (s, 6 H), 2.10 (s, 6 H), 2.1 (m, 1 H); MS m/z 262 (M^+, 0.5), 202 (12), 160 (100), 143 (27), 91 (8), 43 (36). Anal. Calcd for $C_{15}H_{18}O_4$ (262.31): C, 68.68; H, 6.92. Found: C, 68.45; H, 7.11. **1-Acetoxy-2,2,5,6-tetramethylindan (5, R = Me)**: ^{1}H NMR (200 MHz) δ 7.12 (s, 1 H), 6.99 (s, 1 H), 5.74 (s, 1 H), 2.86 (d, J = 15.4, 1 H), 2.58 (d, J = 15.4, 1 H), 2.24 (s, 6 H), 2.07 (s, 3 H), 1.12 (s, 3 H), 1.10 (s, 3 H); MS m/z 232 (M^+, 3), 172 (100), 157 (33), 143 (12), 128 (17), 91 (7), 77 (7), 43 (37). Anal. Calcd for $C_{15}H_{20}O_2$ (232.32): C, 77.55; H, 8.68. Found: C, 77.87; H, 8.79.

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Oxidation with CAN. Typically, α-substituted *p*-xylene (1) (3.3 mmol) and CAN (3.3 mmol) in acetic acid (100 mL) were made to react at 60 °C under nitrogen atmosphere until the orange color faded. The mixture was cooled and extracted with light petroleum, and the collected organic extracts were washed with aqueous $NaHCO_3$ then with water and finally dried with anhydrous Na_2SO_4.

Anodic Oxidation. The electrochemical experiments were performed in a thermostated microcell at 25 °C with platinum electrodes (12 cm^2 effective area). The magnetically stirred solution of the α-substituted xylene (2.1 mmol) in 3:1 v/v acetic acid/acetonitrile mixture were electrolyzed at constant potential (between 1.7 and 2.3V, vs SCE) by using an AMEL system 5000 potentiostat until 1 F/mol, in some cases 0.2 F/mol, of charge were passed. Some experiments were carried out at constant current (5 mA/cm^2). The reaction mixture was then worked up as above. The current yields, determined by GC or by ^1H NMR analysis using, respectively, *tert*-butylbenzene and diphenylmethane as internal standard, ranged from 40 to 100%.

Determination of the Isomeric Distribution. The isomeric distribution of Z-substituted benzyl acetates obtained from the anodic and CAN-promoted oxidations of 1 was determined by GC analysis. The isomer ratio was calculated against a calibrated solution of authentic specimens.

Determination of E_p values. E_p values (vs SCE) have been determined by cyclic voltammetry (100 mV/s) under nitrogen, at a platinum disk electrode in acetonitrile (HPLC grade) with ca. 0.1 M tetra-*n*-butylammonium tetrafluoborate as the supporting electrolyte, using an Amel System 5000 potentiostat.

Acknowledgment. The financial support of the Ministry for the University and the Scientific and Technological Research (MURST) is gratefully acknowledged.

Registry No. 1 (Z = OH), 589-18-4; 1 (Z = OCH_3), 3395-88-8; 1 (Z = CH_3), 622-96-8; 1 (Z = CN), 2947-61-7; 1 (Z = COOMe), 23786-13-2; 1 (Z = OAc), 2216-45-7; 1 (Z = *t*-Bu), 24797-40-8; $1^{\bullet+}$ (Z = OH), 105639-65-4; $1^{\bullet+}$ (Z = OCH_3), 136708-11-7; $1^{\bullet+}$ (Z = CH_3), 73089-22-2; $1^{\bullet+}$ (Z = CN), 130932-66-0; $1^{\bullet+}$ (Z = COOMe), 136708-12-8; $1^{\bullet+}$ (Z = OAc), 136708-13-9; $1^{\bullet+}$ (Z = H), 34510-22-0; $1^{\bullet+}$ (Z = *t*-Bu), 136708-14-0; 2 (Z = CH_3), 19759-40-1; 2 (Z = CN), 75599-81-4; 2 (Z = COOMe), 136707-99-8; 2 (Z = OAc), 2929-93-3; 2 (Z = *t*-Bu), 136708-00-4; 3 (Z = CH_3), 67035-84-1; 3 (Z = CN), 80364-28-9; 3 (Z = COOMe), 119991-78-5; 3 (Z = OAc), 14720-70-8; 3 (Z = *t*-Bu), 136708-03-7; 4 (R = CH_3), 136707-98-7; 4 (R = H), 1075-22-5; 5 (R = CH_3), 136708-07-1; 5 (R = H), 136708-04-8; 6 (R = CH_3), 136708-02-6; 6 (R = H), 136708-01-5; ceric ammonium nitrate, 10139-51-2; *cis*-1,3-diacetoxy-5,6-dimethylindan, 136708-05-9; *trans*-1,3-diacetoxy-5,6-dimethylindan, 136708-06-0; α-hydroxy-*p*-tolylacetonitrile, 4815-10-5; α,α′-dibromo-*p*-xylene, 4076-57-7; *p*-tolyl *tert*-butyl ketone, 30314-44-4; 5-methylindan-1,3-dione, 50919-77-2; 5-methylindan, 874-35-1; 5-bromo-6-methylindan, 136708-08-2; 4-bromo-5-methylindan, 136708-09-3; 4-(acetoxymethyl)-5-methylindan, 136708-10-6.

Friedel–Crafts Alkylation of Benzenes Substituted with Meta-Directing Groups

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Received January 3, 1991

In protonic acids, benzaldehyde, acetophenone, benzophenone, and ethyl benzoate were ring-alkylated by alcohols. Benzonitrile was N-alkylated rather than ring-alkylated. Ethyl *n*-propyl, isopropyl, and *n*-butyl alcohol were effective alkylating agents, whereas methyl and *tert*-butyl alcohol were not. Alkylations with *n*-propyl and *n*-butyl alcohol gave products in which the alkyl group was completely rearranged. Sulfuric, polyphosphoric, and 85% phosphoric acid were effective catalysts. The alkylation apparently proceeds via the reaction of an alkyl cation with the unprotonated substrate.

Introduction

Benzenes substituted with meta-directing groups are usually considered to be inert toward Friedel–Crafts alkylation. In an earlier paper[1] we showed that the reason for the apparent inertness is that the most widely used catalysts, e.g., $AlCl_3$, preferentially coordinate with substrate rather than with the reagent. The catalyst thus loses its activity and the substrate is further deactivated by the presence of a positive charge, which is partially distributed on the ring. However, with a properly selected catalyst, one which preferentially coordinates with the reagent rather than with the substrate, benzenes substituted with meta-directing groups are reactive toward Friedel–Crafts alkylation. In fact, in sulfuric acid, even nitrobenzene can be alkylated by ethanol.[1]

Here we will describe how the natures of the substrate, the alcohol, and the catalyst affect the alkylation. Benzaldehyde, acetophenone, benzophenone and ethyl benzoate were all ring-alkylated. Ethyl, *n*-propyl, isopropyl, and *n*-butyl alcohol were effective alkylating agents, whereas methyl and *tert*-butyl alcohol were not. Sulfuric acid, PPA, and 85% phosphoric acid were effective catalysts.

(1) Shen, Y. S.; Liu, H. X.; Chen, Y. Q. *J. Org. Chem.* **1990**, *55*, 3961.

Experimental Section

The reagents were all chemically or analytically pure and were obtained commercially. Benzaldehyde was distilled, and a small amount of hydroquinone was added before use.

Typically, substrate (20 mmol), alcohol (40 mmol), and catalyst (15–20 mL) were mixed and the mixture was heated at 90–110 °C for 12–48 h. The cooled mixture was then poured into water and the whole was extracted thrice with $CHCl_3$. After evaporation of the solvent the product composition and yield were determined by GC/MS. The results were verified by ^1H NMR. The alkylation of benzaldehyde was performed under nitrogen. In the alkylation of ethyl benzoate the first step of workup was to pour the reaction mixture into a mixture of ice, water, and a slight excess of $NaHCO_3$.

Results and Discussion

A. Alkylation of Benzophenone by Various Alcohols. Benzophenone was alkylated by ethyl, *n*-propyl, isopropyl, and *n*-butyl alcohol. The results are summarized

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