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Dediazoniation of 4-Nitrobenzenediazonium Ions in Acidic MeOH/H_2O Mixtures: Role of Acidity and MeOH Concentration on the Formation of Transient Diazo Ethers that Initiate Homolytic Dediazoniation

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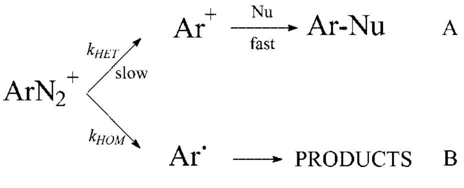
We have investigated the dediazoniation of 4-nitrobenzenediazonium (4NBD) ions in MeOH/H_2O mixtures under acidic conditions at 50 °C employing a combination of spectrophotometric and chromatographic techniques. The kinetic behaviour is quite complex; in the absence of MeOH, the dediazoniations follow first-order kinetics with a half-life $t_{1/2}$ = 1383 min, but the addition of small concentrations of MeOH lead to more rapid but non-first-order kinetics, suggestive of a radical mechanism, with $t_{1/2} \approx 6$ min at 10 % MeOH. Further increases in the MeOH concentration slow down the rate of dediazoniation and reactions progressively revert to first-order behaviour, with clean first-order kinetics at percentages of MeOH higher than 90 % ($t_{1/2} \approx 77$ min). The analyses of the reaction mixtures by HPLC indicate up to four dediazoniation products depending on the particular experimental conditions. These are 4-nitrophenol (ArOH), 4-nitroanisole (ArOMe), nitrobenzene (ArH), and 4,4′-dinitrobiphenyl (DNB), this last product being detected only at MeOH percentages in the range 0.5–15 %. In the absence of MeOH, ArOH is the only product and formed in quantitative yield; however, at only 20 % MeOH, ArOH is down to less than 10 % and the reduction product, ArH, is obtained in more than 90 %. Upon increasing the MeOH content further, the formation of ArOMe becomes competitive and, at 99 % MeOH, both ArH (60 %) and ArOMe (40 %) are obtained. The observed rate constants, $k_{\text{obsd.}}$, or half-lives, $t_{1/2}$, are the same regardless of whether they are determined by monitoring product formation (by a well-established product derivatization protocol followed by HPLC measurements) or reactant decomposition (obtained UV spectrophotometrically). At any given MeOH content, the plot of $k_{\text{obsd.}}$ or $t_{1/2}$ values against the acidity (defined as –log [HCl]) is S-shaped, the inflexion point depending upon the MeOH concentration. The complex behaviour can be accounted for by two competitive mechanisms, and whichever is dominant depends upon the acidity and the composition of the aqueous methanol solvent. Furthermore, the acid-dependence of the switch between the homolytic and heterolytic mechanisms suggests the homolytic dediazoniation proceeds via transient diazo ethers. Thus, the MeOH molecules react with ArN_2^+ to yield an O-coupling adduct in a highly unstable *Z* configuration, i.e. a (*Z*)-diazo ether. Subsequently, this undergoes homolytic fragmentation which initiates a radical process. In the polar alternative, the methanol simply solvates the ArN_2^+ ions, allowing them to undergo thermal heterolysis, i.e. a $D_N + A_N$ mechanism via the aryl cation.

Introduction

Arenediazonium ions, ArN_2^+, are among the most useful reagents in aromatic organic chemistry because the versatile diazonium group can be readily replaced by numerous other groups.[1–4] This so-called dediazoniation reaction can take place by a heterolytic pathway, Scheme 1 (A), characterized by the intermediacy of aryl cations in a $D_N + A_N$ mechanism,[4–9] or by a homolytic pathway involving aryl radicals,[4,5,10] Scheme 1 (B). In addition to the well-known applications in synthetic and azo-dye chemistry, new and interesting applications of arenediazonium salts are emerging, e.g. they are currently being used to modify carbon



Scheme 1. Basic representation of the dediazoniation mechanisms: (A) heterolytic, i.e. $D_N + A_N$; (B) homolytic.

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surfaces,[11] to probe interfacial compositions of colloidal aggregates,[12] and to assess the distribution of polar molecules in emulsions.[13] However, their use is not without potential hazard; under some conditions, some may be dangerously thermally unstable[2] and the role of some in carcinogenic and mutagenic processes is being explored.[14]

ArN_2^+ ions may function readily as Lewis acids, the β-nitrogen being the site of electrophilic reactivity, to give covalently bonded adducts, ArN_2–Nu, with Lewis bases (nucleophiles), Nu^- (or NuH, followed by loss of a proton).[4,5] Typical examples of these reactions are the formation of azo dyes, where N- and C-coupling reactions take place; but other atoms such as oxygen, sulfur, and phosphorus may also be involved leading to the so-called O-, S-, and P-coupling reactions.[4,5] Coupling with oxygen has been mostly observed under experimental conditions allowing appreciable concentrations of the anionic forms of the nucleophiles, e.g. when OH^-, RCO_2^-, RN_2O^-, RO^-, or ascorbate ions are present in the reaction mixture.[15–17]

The addition of arenediazonium cations to alkoxide and phenoxide anions is an O-coupling reaction that has been well investigated.[4,5] Bunnett and co-workers postulated that, in alkaline methanolic solutions, the reaction takes place through the kinetically controlled formation of a highly unstable (*Z*)-diazo ether that can either isomerize to yield the thermodynamically stable (*E*)-diazo ether, or undergo homolytic scission leading to reduction products.[18,19] Under acidic conditions, the same researchers postulated that hydrodediazoniations take place by direct electron transfer from the solvent to the arenediazonium ion;[18] however, no convincing evidence for this, or other mechanistic alternatives, was provided and the initiation process of solvent-induced hydrodediazoniations has remained a matter of debate for a long time because no obvious reductants were employed in those experiments.[4,10]

In recent solvolytic dediazoniation work,[20] we found S-shaped variations in both $k_{obsd.}$ and product formation with acidity for toluenediazonium ions. The results allowed us to conclude that the initiation pathways of the solvent-induced homolytic dediazoniations is not an electron transfer from the solvent but proceeds through the formation of a transient O-diazo ether in a rapid preequilibrium step which decomposes homolytically initiating a radical mechanism.

Here, we report an extension to our solvolytic studies by a detailed investigation of the methanolyses of *p*-nitrobenzenediazonium ions (4NBD) in the whole MeOH/H_2O composition range at different acidities to probe further the proposed initiation mechanism. For this purpose, spectrophotometric and chromatographic techniques were employed. 4NBD was chosen because it is well recognized that substituents in the aromatic ring of diazonium ions have important mechanistic effects.[7,8,21] For instance, electron-withdrawing substituents in the 4-position destabilize the aryl cation by induction more than they destabilize the parent arenediazonium ions, and therefore its spontaneous decomposition reaction is much slower than that of the parent, or of arenediazonium ions bearing electron-releasing groups such as Me.[22,23]

Changes in the concentration of electrolytes (e.g., Cl^-, $CuCl_2$, or H_3O^+) have a negligible effect on the rate constant and the dediazoniation product distribution of toluenediazonium ions.[23] In contrast, dediazoniation rate constants and the product distribution for 4NBD decomposition are significantly modified; for example, $CuCl_2$ catalyzes 4NBD decomposition and leads to the formation of large amounts of *p*-chloronitrobenzene at the expense of 4-nitrophenol.[22] Electron-withdrawing substituents (as opposed to methyl, for example) in the aromatic ring make the arenediazonium ions prone to decompose through homolytic pathways and to form transient O-diazo ether derivatives in the presence of β-cyclodextrin[24,25] or ascorbic acid;[15] for both nucleophiles, the adducts were detected experimentally and, in some instances, isolated.[26]

Results

1. Effects of the Percentage of MeOH on the Rate of Decomposition of 4NBD

The effect of solvent composition on the observed rate constant, $k_{obsd.}$, in the presence of 0.001 M HCl (which is at least 10 times greater than the initial concentrations of substrate) was investigated by changing the percentage of MeOH in the reaction mixture. In the absence of MeOH,

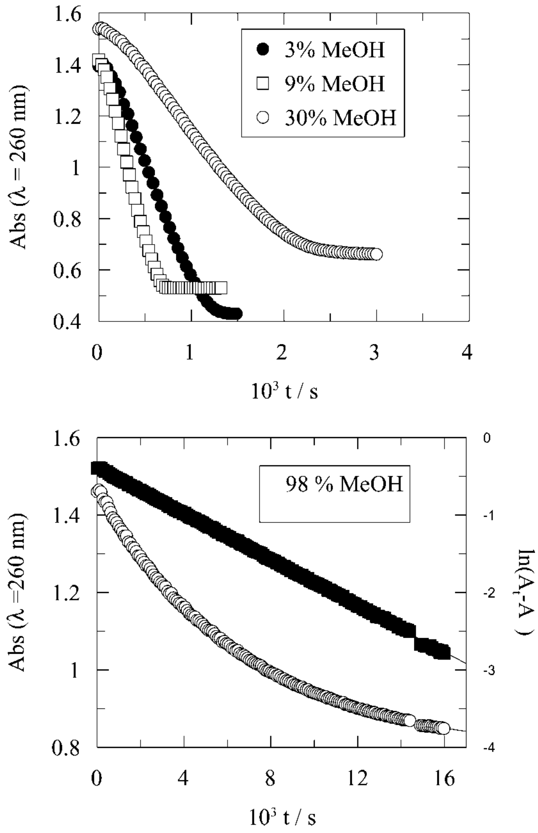


Figure 1. Variation of the absorbance at λ = 260 nm with time in different MeOH/H_2O mixtures. $[4NBD]_o \approx 1 \cdot 10^{-4}$ M, [HCl] = 10^{-3} M, *T* = 50 °C.

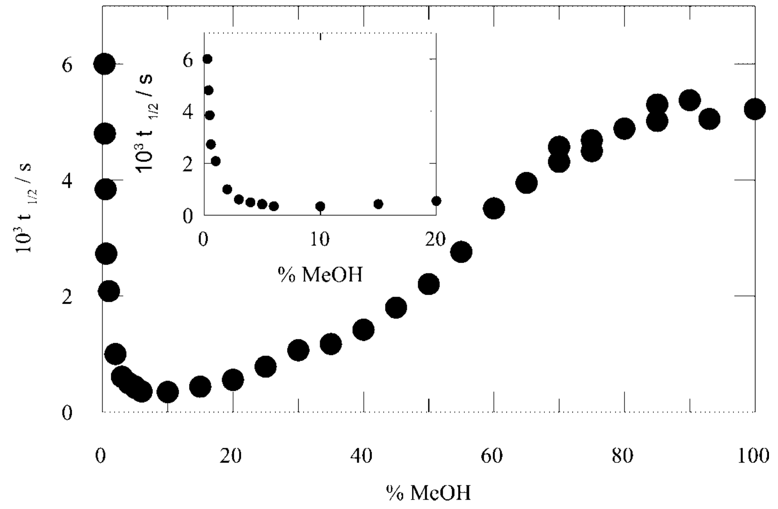


Figure 2. Variation of $t_{1/2}$ with the percentage of MeOH for solvolyses of 4NBD. Experimental conditions are as in Figure 1.

the thermal decomposition of 4NBD follows clean first-order kinetics for more than three half-lives, as previously reported, with $k_{\text{obsd.}} = 8.26 \cdot 10^{-6}\ s^{-1}$.[22,27] Surprisingly, addition of only small amounts of MeOH results in the UV absorbance against time plots becoming S-shaped (Figure 1), which is clearly not compatible with simple first-order kinetics and suggests intrusion of a radical process. Careful purification of the diazonium salt, and changes in the batches of the MeOH employed to prepare the reaction mixtures and of the MeOH supplier, did not result in significant changes in the observed kinetic behavior, indicating that the results obtained are not due to possible impurities in the MeOH.

Interestingly, upon increasing further the percentage of MeOH, the reaction profiles gradually became first order again; at percentages higher than 90% MeOH, clean first-order kinetics are again obtained, with $k_{\text{obsd.}} = 1.5 \cdot 10^{-4}\ s^{-1}$ in 98% MeOH, Figure 1, i.e. $k_{\text{obsd.}}$ is about 18 times higher in 98% MeOH than in pure water. It is worth noting that the $k_{\text{obsd.}}$ value obtained in 99.5% MeOH is in excellent agreement with a literature value obtained in acidic MeOH under N_2,[28] $k_{\text{obsd.}} = 1.54 \cdot 10^{-4}\ s^{-1}$.

Because of the non-first-order behaviour obtained at intermediate MeOH percentages, but wishing to compare the effect of the percentage of MeOH on the rate of the reaction, we report half-lives values ($t_{1/2}$) that are plotted instead of $k_{\text{obsd.}}$ in Figure 2. In aqueous acid solution, in the absence of MeOH, $t_{1/2} \approx 1383$ min (not included in Figure 2), consistent with remarkable thermal stability of 4NBD compared with other arenediazonium ions,[7,22,28] but addition of small amounts of MeOH speeds up the reaction appreciably with $t_{1/2}$ values decreasing to a minimum of about $t_{1/2} = 6$ min at 10% MeOH. Further addition of MeOH causes $t_{1/2}$ to increase smoothly up to about $t_{1/2} =$ 77 min at 99.7% MeOH. The inset in Figure 2 is an expansion of the results obtained in the range 0–20% MeOH.

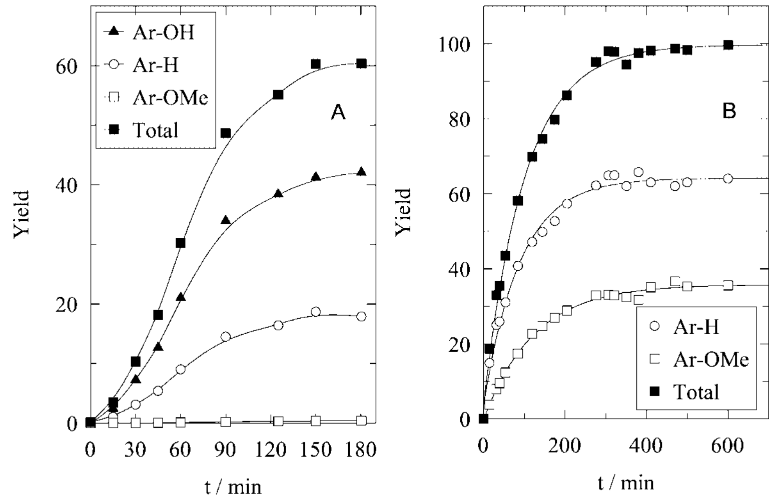


Figure 3. Changes in the percentages of products with time determined by HPLC: (A) 0.5% MeOH; (B) 99.97% MeOH. Other conditions are as in Figure 1.

2. Kinetics of Product Formation

The observed rate constants for the product formation were obtained chromatographically by following a published procedure[29] at selected percentages of MeOH. Figure 3 includes representative plots showing the formation of products with time at 0.5% MeOH (Figure 3, A) and 99.7% MeOH (Figure 3, B). At 0.5% MeOH, HPLC chromatograms (not shown) showed signals for three anticipated products (ArOH, ArH, and ArOMe) plus one due to a compound subsequently shown to be 4,4′-dinitrobiphenyl, DNB; see Exp. Sect. for peak identification. At 99.7% MeOH, only peaks for ArOMe, ArOH, and ArH were detected, ArOMe and ArH being the major ones.

At 0.5% MeOH (Figure 3, A) the product formation does not follow first-order kinetics; S-shaped curves are obtained with a $t_{1/2}$ value of 60 min for the formation of either ArOH or ArH (or the total). The change with time of the chromatographic signal due to DNB (not shown) follows a similar profile with the same $t_{1/2}$ as that for the other products (Figure 3, A). Note that the $t_{1/2}$ value obtained for product formation is identical with that obtained spectrophotometrically for ArN_2^+ loss, Figure 2. At 99.7% MeOH (Figure 3, B) formation of products follows clean first-order behaviour and only two out of three dediazoniation products, ArH and ArOMe, are formed in appreciable quantities; conversion to these products is essentially quantitative. The observed rate constant for ArH formation is the same, within experimental error, to that for ArOMe formation, the average value $k_{obsd.} = (1.6 \pm 0.1) \cdot 10^{-4}\ s^{-1}$ ($t_{1/2} = 4313 \pm 332$ s) being in excellent agreement with that reported by Kuokkanen for reaction under N_2,[28] and with that obtained for ArN_2^+ loss obtained spectrophotometrically, Figure 1, B and Figure 2.

HPLC kinetics results thus show that homolytic and heterolytic products are formed with rate constants the same as for disappearance of 4NBD ions, strongly suggesting competitive mechanisms.

3. Effects of Acidity on the Rate of the Reaction

The effects of acidity on $k_{obsd.}$ or $t_{1/2}$ were investigated at different percentages of MeOH, Figure 4. At high percentages of MeOH, S-shaped profiles are obtained, indicating that the acidity of the reaction has a significant effect on the reaction mechanism. It was not possible, however, to obtain a complete sigmoidal profile at low percentages of MeOH because of the much higher HCl concentrations needed (Figure 4, C), but the data obtained are suggestive of a similar S-shaped profile. Parallel variations were observed in the ethanolyses[20] and butanolyses[30] of toluenediazonium ions and attributed to the formation of a transient diazo ether intermediate from the arenediazonium ions which then leads on to the reduction product ArH, Scheme 2.

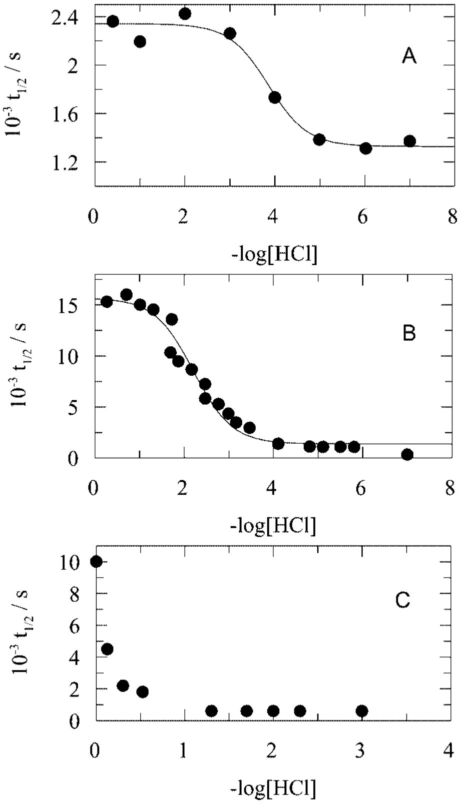
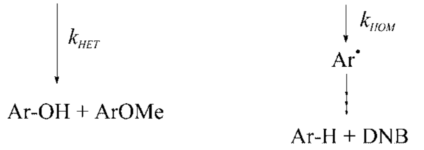


Figure 4. Variation in $t_{1/2}$ with acidity, defined as –log[HCl], at different percentages of MeOH: (A) 95%; (B) 80%; (C) 5%. Other experimental conditions are as in Figure 1. Solid lines were obtained by fitting the data to a titration curve of the Henderson–Hasselbach type.



Scheme 2. Proposed competitive heterolytic and homolytic dediazoniation mechanisms.

4. Effects of Solvent Composition on Dediazoniation Product Distribution

The effect of solvent composition on the product distribution was investigated by measuring the product yields at different percentages of MeOH when dediazoniation was complete. Up to four dediazoniation products, ArH, ArOH, ArOMe, and DNB were detected, and conversion to products is quantitative. Because DNB is only formed at low percentages of MeOH, its yield is not shown in Figure 5 for the sake of clarity, nor included in the "total yield".

Figure 5 shows the variations in the yields of the three main dediazoniation products, ArOH, ArH, and ArOMe, with solvent composition. The yield of ArOH drops very fast from virtually 100% to only 8% at 15% MeOH, with

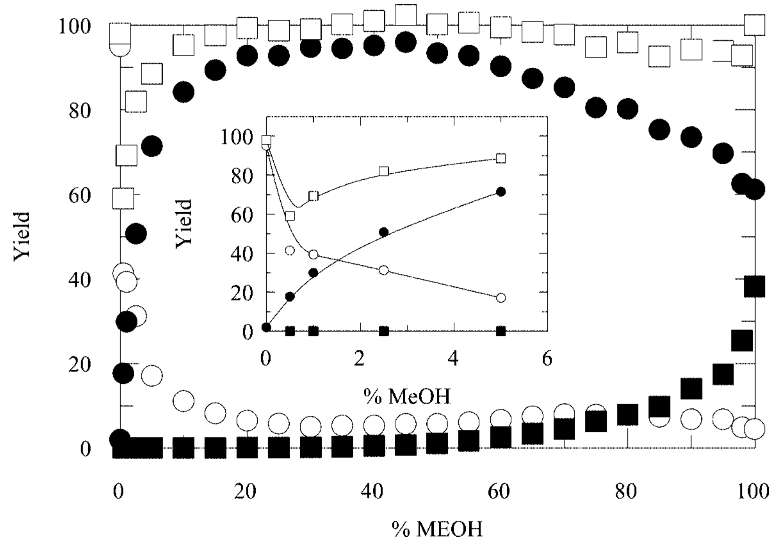


Figure 5. Variation in the product distribution with the percentage of MeOH for the methanolysis of 4NBD: ○; Ar–OH: ●; Ar–H: ■; Ar–OMe: □, total. Inset: amplification of the results at low percentages of MeOH; note that, under these conditions, 4,4′-dinitrobiphenyl is also formed (but not shown here). See text and Exp. Sect. for product identification and HPLC details; other conditions are as in Figure 1.

a concomitant increase in the yield of the reduction product (90% at 15% MeOH) and DNB. Thereafter, however, the yield of ArOH is remarkably constant. Figure 5 also shows that the variation in the yield of ArOMe with MeOH concentration, increasing from about 40% MeOH, is principally at the expense of the reduction product, ArH. At percentages of MeOH close to 100%, about 60% of ArH and 40% of ArOMe are obtained, in agreement with previous results obtained by De Tar and Kosuge.[31]

Discussion

Solvolytic dediazoniation studies in a variety of solvents[4,5,10] indicate that MeOH, EtOH, and DMSO are usually borderline solvents where both homolytic and heterolytic mechanisms can be observed simultaneously depending on experimental conditions and the nature of substituents in the arenediazonium ions. Previous studies on the methanolyses of 4-toluenediazonium ions under experimental conditions similar to those employed in this work indicate that reactions are first order throughout the whole composition range,[23,32] with $k_{\text{obsd.}}$ values increasing 2–3 fold on going from 0 to 100% MeOH. And, although the reduction product (toluene) was detected, its yield was reported to be less than 10% indicating that heterolysis is the predominant mechanism.

Earlier reports of solvolytic investigations with electron-withdrawing substituents pointed out that reactions in alcohols such as EtOH and trifluoroethanol (TFE) are qualitatively different from those in more ionizing media (although TFE is actually a fairly ionizing medium) because of the appreciable amounts of hydrodediazoniation products formed.[7,8,21,22,27] Many investigators have sought to determine the mechanisms by which the diazonium group is replaced by hydrogen in solvolytic dediazoniations to yield Ar–H derivatives.[4,5,33,34] The source of electrons in solvolytic dediazoniations has been reported to be the solvent.[7,8,10,35] However, in contrast to other dediazoniations, no obvious reductants are employed in these experiments to initiate the radical process and hence the mechanism and nature of the initiation step has been a matter of debate for a long time.[4,9,10,19,34]

We recently proposed[20,30] that the initiation process of the homolytic pathway follows the formation of a highly unstable transient diazo ether and is not by a direct electron transfer from the solvent (EtOH) to the arenediazonium ion.[19,33] The S-shaped variations in $k_{\text{obsd.}}$ with –log[HCl] shown in Figure 4 are consistent with such a hypothesis because they are suggestive of reactions of acid–base conjugate pairs where both forms are attainable but show different reactivities, i.e., two competitive mechanisms as shown in Scheme 2. These comprise the thermal heterolytic decomposition of solvated ArN_2^+ ions by the $D_N + A_N$ mechanism and a rate-determining fragmentation of a transient diazo ether (ArN_2OMe) formed from ArN_2^+ ions and MeOH molecules in a solvation shell in a rapid pre-equilibrium step. Under our experimental conditions, only two species may undergo acid-base processes, MeOH ($pK_a \approx 15$) and the ArN_2^+ ions, which may give rise to the diazoic acid, Ar–N=N–OH; pK_a values for 4NBD have been reported to be ca. 6.3,[24,36] so it appears unlikely that ArN_2^+ ions react with MeO^- or with OH^- ions under the present conditions, as they do in alkaline media.[18,19,33]

Similar mechanisms have been employed to interpret the reactivity of arenediazonium ions with a number of ascorbic acid derivatives where the formation of a diazo ether intermediate was detected experimentally by employing electrochemical methods.[15,17] The assumption of a rate-limiting decomposition of the diazo ether is also consistent with reported results for other O-coupling reactions,[4,5,18,37] and was probed experimentally in reactions of arenediazonium ions where geometric restrictions apply.[24,38] From Scheme 2, Equation (1) can be derived where k_{HET} and k_{HOM} are the rate constants for the spontaneous thermal heterolytic decomposition of $\mathrm{ArN_2}^+$ and that for the decomposition of the diazo ether, respectively, and $K_1 = K$ [MeOH] with K standing for the equilibrium constant for diazo ether formation shown in Scheme 2.

$$k_{obs} = \frac{k_{HET}\left[H^+\right] + k_{HOM} K_1}{K_1 + \left[H^+\right]} \qquad (1)$$

This equation is typical of processes where an S-shaped dependence of $k_{\mathrm{obsd.}}$ with $-\log[\mathrm{H}^+]$ is observed (where $[\mathrm{H}^+]$ represents the concentration of protonated solvent molecules). From Equation (1), and by considering limits, we find that when $[\mathrm{H}^+] >> K_1$, $k_{\mathrm{obsd.}} \approx k_{\mathrm{HET}}$, i.e., the reaction proceeds wholly through the $\mathrm{D_N} + \mathrm{A_N}$ mechanism and only heterolytic products are obtained. On the other hand, when $[\mathrm{H}^+] << K_1$, $k_{\mathrm{obsd.}} \approx k_{\mathrm{HOM}}$, i.e. the reaction proceeds wholly through the O-diazo ether and formation of reduction products is favoured. Solid lines in Figure 4 (A) and Figure 4 (B) were obtained by fitting the data to a titration curve of the Henderson–Hasselbach type, from where values of $\mathrm{p}K_1$ = 4.18 (95% MeOH) and 2.2 (80% MeOH) can be obtained. Fitting parameters are listed in Table 1. Thus, increasing concentrations of MeOH have opposing effects upon the formation of the diazo ether in this concentration range: it is favoured modestly by higher concentrations of MeOH through the mass action effect, but strongly opposed by the medium effect on the equilibrium constant. It was not possible to determine $\mathrm{p}K_1$ values at low MeOH content, see Figure 4 (C), but the data suggest that the inflexion point should be reached at [HCl] > 1 M. Variations in $\mathrm{p}K_1$ values with the percentage of alcohol were previously observed[20] but were not as large as in the present case.

Table 1. Kinetic parameters obtained by fitting the data in Figure 4 (A) and Figure 4 (B) to a modified Henderson–Hasselbach equation. The parameters $t_{1/2}$ (HET) and $t_{1/2}$ (HOM) refer to the fitted values at high and low acidity, respectively; $t_{1/2}$ values at 95% MeOH were determined from the first-order rate constants for the sake of comparisons.

% MeOH	$\mathrm{p}K_1$	$t_{1/2}$ (HET) [s]	$t_{1/2}$ (HOM) [s]
95	4.18	1824	3648
80	2.20	1375	15687

It appears evident, therefore, that the formation of the transient diazo ethers depends on both pH and MeOH concentration, and that at low percentages of MeOH the diazo ether is formed because of the low acidities employed (i.e., the high K_1 value for the formation of the transient diazo ether) and the reaction proceeds through a radical mechanism. In contrast, its formation is not so favoured at high percentages of MeOH in spite of the much higher MeOH concentrations present in the reaction mixture; in these situations, MeOH molecules simply solvate $\mathrm{ArN_2}^+$ ions and the ionic mechanism becomes competitive with the radical one leading to the results shown in Figure 3 (B) and Figure 5.

We thus propose that the initiation step in homolytic dediazoniations induced by the solvent is the unimolecular decomposition of the transient diazo ether, yielding $\mathrm{Ar}^{\bullet}$ and $^{\bullet}\mathrm{OMe}$; the experimental observations can then be rationalized by adapting the currently assumed radical propagation mechanism[8,19,33,39] by including as the initiation step the homolytic fragmentation of the transient diazo ether, Scheme 3.

$$\mathrm{Ar\text{-}N_2}^+ + \mathrm{MeOH} \xrightleftharpoons{K} \mathrm{Ar\text{-}N{=}NOMe} + \mathrm{H}^+ \qquad 1$$

$$\mathrm{Ar\text{-}N{=}NOMe} \xrightarrow{k_{HOM}} \mathrm{Ar}^{\bullet} + {}^{\bullet}\mathrm{OMe} + \mathrm{N_2} \qquad 2$$

$$\mathrm{Ar}^{\bullet} + \mathrm{Me\text{-}OH} \longrightarrow \mathrm{ArH} + {}^{\bullet}\mathrm{CH_2\text{-}OH} \qquad 3$$

$$2\ {}^{\bullet}\mathrm{CH_2\text{-}OH} \longrightarrow \mathrm{CH_3\text{-}OH} + \mathrm{CH_2O} \qquad 4$$

$$2\ \mathrm{Ar}^{\bullet} \longrightarrow \mathrm{Ar\text{-}Ar} \qquad 5$$

$$\mathrm{Ar}^{\bullet} + {}^{\bullet}\mathrm{OMe} \longrightarrow \mathrm{ArOMe} \qquad 6$$

Scheme 3. Proposed radical mechanism for the homolytic reaction of arenediazonium ions with alcohols.

Once the aryl radical is formed after homolytic fragmentation of the transient diazo ether in steps 1–2, the $\mathrm{Ar}^{\bullet}$ radicals partitions between competing product-forming routes. At low percentages of MeOH, an aryl radical reacts with another aryl radical to yield 4,4′-dinitrobiphenyl, step 5, as was found experimentally, and the reaction terminates. At higher MeOH concentrations, when MeOH becomes an important part of the solvation shell, the aryl radical reacts with a MeOH molecule within the solvent cage by abstracting a hydrogen atom, and this is followed by disproportionation of the hydroxymethyl radicals to yield formaldehyde as a final by-product in this termination route.

It was reported[8] that, in ethanolyses of $\mathrm{ArN_2}^+$ ions bearing electron-withdrawing substituents, hydrodediazoniations are invariably accompanied by the formation of some aryl ethyl ether in spite of the very large difference between the homolytic and heterolytic rate constants. To rationalize this observation, it was proposed that the ethyl ethers may be formed by the product-forming path 6 in Scheme 3, which competes with the main hydrodediazoniation path. Evidence coming from different directions suggests that this is not a major pathway for the formation of ArOMe under our experimental conditions, although it cannot be completely ruled out. At percentages between 5–60% MeOH, the homolytic pathway is predominant because of the very low $t_{1/2}$ values compared to that in absence of MeOH, Figure 2, and because only ArH is obtained in significant yields, Figure 5. It follows, therefore, that if ArOMe is being formed by the homolytic pathway 6 in Scheme 3, appreciable yields should have been detected within this MeOH range but were not.

As discussed before, in aqueous acid solution in the absence of MeOH, the thermal decomposition of 4NBD is very slow, $t_{1/2}$ = 1383 min, but addition of even low concentrations of MeOH increases the overall rate because of the intervention of the homolytic route via the formation of the transient diazo ether and its subsequent fragmentation. At percentages of MeOH higher than 20%, the observed $t_{1/2}$ increases again, i.e. the reaction becomes slower, although there are two opposing effects. On the one hand, the equilibrium constant for formation of the transient diazo ether decreases but, on the other hand, the mass action effect will promote formation of the diazo ether. Results in Table 1 show that observed $t_{1/2}$ values for the heterolytic pathway [i.e., when $[H^+] >> K_1$, Equation (1)] increase upon increasing the MeOH content of the solution, as is found with other arenediazonium ions, for example, the methyl derivatives,[7–9] but observed $t_{1/2}$ values for the homolytic pathway (i.e., when $[H^+] << K_1$) decrease upon increasing the percentage of MeOH. So, the heterolytic pathway becomes increasingly more competitive with respect to the homolytic one and because this happens at high [MeOH], larger amounts of ArOMe than ArOH are expected and are observed, see Figure 5.

According to Scheme 2, $k_{obsd.}$ is given by Equation (1), and the ratio of yields of homolytic to heterolytic products is given by Equation (2).[40]

$$\frac{Y_{HOM}}{Y_{HET}} = \frac{k_{HOM} K_1}{k_{HET}\left[H_3O^+\right]} \qquad (2)$$

Hence, if one assumes that ArOH and ArOMe are formed exclusively by the heterolytic route, the ratio of the total yields of homolytic products to the heterolytic ones is $Y_{HOM}/Y_{HET} \approx 2.9$ at 95% MeOH (HPLC data not shown). From Figure 4 (A), $pK_1 = 4.18$ and from Equation (2) with $[H_3O^+] = 10^{-3}$ M, it follows that $k_{HOM}/k_{HET} \approx 44$. By taking into consideration Equation (1), one can obtain values for the homolytic and heterolytic rate constants at 95% MeOH, $k_{HET} = 3.3 \cdot 10^{-5}\ s^{-1}$ and $k_{HOM} = 1.4 \cdot 10^{-3}\ s^{-1}$. The determined k_{HET} value represents an increase of 4–fold on going from water, i.e., absence of MeOH, to 95% MeOH, an increase higher than that observed for other arenediazonium ions in acidic aqueous methanol mixtures, where increases in k_{HET} of about twofold were reported.[23] For the ionic mechanism, Scheme 1 (A), a rate-limiting nucleophilic attack that would lead to a much stronger dependence of k_{HET} with solvent composition than that observed; our data are thus consistent with an ionic mechanism in which the rate-limiting step is the formation of a highly unstable aryl cation, Scheme 1 (A), in agreement with the previous reports based on the behavior of other ArN_2^+ ions in alcohol-water mixtures.[7–9]

Focusing on the ionic mechanism, data in Figure 5 indicate that, at approximately 80% MeOH/H_2O, yields of ArOH and ArOMe are the same. Therefore, the selectivity of the electrophilic intermediate in the reaction towards water and MeOH as competing nucleophiles is given by $S_W^{MeOH} = [H_2O]/[MeOH] = 0.56$, a value very similar to those found from reactions of other arenediazonium ions with different non-ionic nucleophiles.[12,41] Such a value is orders of magnitude lower than those observed for anionic nucleophiles competing with water for stabilized carbocations[42,43] and is consistent with the reactivity-selectivity principle, Scheme 1 (A), i.e., rate-determining formation of a highly reactive electrophilic intermediate.

Conclusions

In conclusion, we have been able to rationalize the complicated behaviour found for the aqueous methanolysis of 4-nitrobenzenediazonium ions under acidic conditions. The reaction provides an excellent example of the influence of solvent composition on the change from a heterolytic mechanism to a homolytic one. In the present case, this change can be accommodated by a mechanism in which a solvent molecule acts either as a nucleophile that simply solvates the diazonium ions (allowing them to undergo thermal heterolytic decomposition), or it may react directly with them to yield O-coupling adducts in a highly unstable *Z* configuration, i.e. (*Z*)-diazo ethers (which then undergo homolytic fragmentation initiating radical processes). In the present case, it appears therefore, that there is no conversion of the unstable (*Z*)-diazo ether to the much more stable *E* isomer, which would eventually undergo acid-catalyzed fragmentation.[4–9] The proposed mechanism accounts for the kinetic parameters, the reduction product formation, the ether formation, the rate-enhancing effect of electron-withdrawing substituents in the aromatic ring and the non-first-order kinetics observed at intermediate percentages of MeOH because at low-moderate MeOH percentages, the rate of disappearance of ArN_2^+ depends on the concentration of methoxy radicals and, at low percentages of MeOH, on the concentration of Ar radicals (path 4 and 6 in Scheme 3).

A preliminary analysis of the pK_1 values found in this work, together with those previously reported,[20] appears to suggest that the formation of the O adducts depends on the nature of the alcohol employed as well as on alcohol concentration, the acidity of the medium, and the nature of the substituent in the benzene ring of the diazonium ions. Further investigations into the formation of diazo ethers are in progress and will be the subject of future reports.

Finally, it is worth noting that the results obtained here indicate a simple, effective, and quick practical method for replacing an aromatic primary amino group by hydrogen. It represents an improved alternative to the method using hypophosphorous acid as reducing agent proposed by Kornblum.[44] Because arenediazonium salts can be prepared easily from readily available aromatic primary amines, these deamination processes involving reductive removal of the primary amine groups are particularly useful in synthetic aromatic chemistry because of the strong directing effects associated with amine substituents.[45,46]

Experimental Section

Instrumentation: UV/Vis spectra and some kinetics experiments were followed with a Beckman DU-640 spectrophotometer equipped with a thermostatted cell carrier and attached to a computer for data storage. Product analysis was carried out with a WATERS HPLC system which included a model 560 pump, a 717 automatic injector, a 2487 dual-wavelength detector, and a computer for control and data storage. Products were analysed with a Microsorb-MV C-18 (Rainin) reverse-phase column (25 cm length, 4.6 mm internal diameter, and 5 µm particle size) using a mobile phase of 70:30 v/v MeOH/H_2O containing 10^{-4} M HCl. The injection volume was 25 µL in all runs and the UV detector was set at 220 and 280 nm.

Materials: 4-Nitrobenzenediazonium (4NBD) tetrafluoroborate was prepared under non-aqueous conditions as described elsewhere,[47] and recrystallized three times from CH_3CN/cold diethyl ether; it was stored in the dark at low temperatures to minimize its decomposition and was recrystallized periodically. 4-Nitrophenol (ArOH), 4-nitroanisole (ArOMe), nitrobenzene (ArH), and other reagents including those used in the preparation of arenediazonium salts (as tetrafluoroborates) were of maximum available purity and were used without further purification. The MeOH employed in the kinetic experiments was HPLC grade and was used as received. Solution composition is expressed as percent MeOH by volume. Molar concentrations were calculated by ignoring the small excess volume of mixed solvents.[48] All aqueous solutions were prepared by using Milli-Q grade water.

Methods: Kinetic data were obtained spectrophotometrically and by HPLC. Observed rate constants were obtained by fitting the absorbance-time data for at least three half-lives to the integrated first-order Equation (3) using a non-linear least-squares method in those cases where clean first-order kinetics were observed; otherwise, $t_{1/2}$ values are reported and defined as the time elapsed for the absorbance or concentration of the reactant to decrease to half its initial value, or for the yield of a product to increase to half its final value.

$$\ln\left(\frac{M_t - M_\infty}{M_0 - M_\infty}\right) = -k_{obs}t \qquad (3)$$

All kinetics runs were at 50 °C. Duplicate or triplicate experiments gave average deviations less than 7%. Stock 4NBD salt solutions were prepared by dissolving it in the appropriate acidic (HCl) mixture to minimize diazotate formation;[49] solutions of final concentrations about $1{\cdot}10^{-3}$ M and [HCl] = $3.6{\cdot}10^{-3}$ M were used generally immediately or within 90 min with storage in an ice bath to minimize decomposition. Beer's law plots (not shown) in aqueous and methanolic solutions up to $2.00{\cdot}10^{-4}$ M were linear (cc. $\geq$ 0.999). Spectrophotometric kinetic data were obtained by following the disappearance of the absorbance of ArN_2^+ at λ = 260 nm. Reactions were initiated by adding an aliquot (< 100 µL) of the ArN_2^+ stock solution to the previously thermostatted reaction mixture. HPLC kinetic data were obtained by following a well-established derivatization protocol that exploits the rapid reaction between 4NBD and a coupling agent to yield an azo dye as described elsewhere.[29,47]

Product analysis of reaction mixtures was by HPLC after dediazoniation was complete. Preliminary HPLC experiments showed that three main products are formed, ArOH, ArH, and ArOMe. Linear (cc. >0.999) calibration curves for converting HPLC peak areas, A, into concentrations were obtained for these products by employing commercial samples. Percentage of formation, Y, of dediazoniation products were obtained from the dediazoniation product concentration, $[\text{Analyte}]_\infty$, and the initial diazonium salt concentration, $[ArN_2^+]_o$, estimated by weight, i.e. Y = $100[\text{Analyte}]_\infty/[ArN_2^+]_o$, as described elsewhere.[9,20,33]

At low percentages of MeOH, an unanticipated product was detected. To identify it, dediazoniation was performed at 50 °C on a large scale in a 0.5% MeOH/H_2O reaction mixture containing [HCl] = 1 mM. The reaction products were extracted with diethyl ether and the solvent was evaporated under reduced pressure. The residue was then dissolved in CH_2Cl_2 and chromatographed on a silica gel column (43–63 u, 60 Å). The isolated target compound was identified by ^1H NMR, ^{13}C NMR as 4,4′-dinitrobiphenyl, and the chemical shifts of the hydrogen atoms were positively correlated with those of the directly bonded carbon atoms by HSQC. ^1H NMR (400 MHz, $CDCl_3$): δ = 6.93 (d, J = 9.1 Hz, 4 H, H2, H2′, H6, H6′), 8.14 (d, J = 9.1 Hz, 4 H, H3, H3′, H5, H5′) PPM. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 115.7 (d, C3, C3′, C5, C5′), 126.3 (d, C2, C2′, C6, C6′), 141.1 (s, C4, C4′), 162.0 (s, C1, C1′) PPM.

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