Multi-electron Reduction of Nitrobenzene Derivatives by an Acid-stable NADH Analogue *via* Acid-Catalysed Electron Transfer Radical-chain Reactions

Shunichi Fukuzumi* and Makoto Chiba
Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan

Acid catalysed multi-electron reduction of nitrobenzene derivatives by an acid-stable NADH analogue, 10-methyl-9,10-dihydroacridine, occurs efficiently under mild conditions in the presence of perchloric acid in acetonitrile. Observation of CIDNP spectra as well as detailed kinetic studies on the acid catalysed reduction of nitrobenzene derivatives by $AcrH_2$ and on the acid catalysed electron transfer from the excited state of $[Ru(bpy)_3]^{2+}$ to nitrobenzene derivatives has revealed that the multi-electron reduction of nitrobenzene derivatives by $AcrH_2$ proceeds *via* acid catalysed electron transfer radical-chain reactions in which hydrogen transfer from $AcrH_2$ to radicals produced by the acid catalysed one-electron reduction of nitrobenzene derivatives is the rate determining propagation step.

The redox reactions of 1,4-dihydropyridine derivatives have attracted considerable interest in view of the vital role of dihydronicotinamide adenine dinucleotide (NADH) as an electron source in enzymatic redox reactions which include not only two-electron but also multi-electron reductions of substrates by NADH.[1–4] With respect to multi-electron reduction of organic substrates by NADH model compounds, it has been reported earlier that a typical NADH model compound, 1-benzyl-1,4-dihydronicotinamide, can reduce nitrobenzene to aniline, phenylhydroxylamine, and hydrazobenzene.[5] However, severe reaction conditions (*e.g.* heating at 412 K in neat nitrobenzene) were required to promote the multi-electron reduction.[5] To date, no efficient catalytic systems of multi-electron reduction of organic substrates by NADH model compounds have been reported.

We recently reported that the two-electron reduction of various carbonyl compounds by an NADH analogue occurs efficiently in the presence of perchloric acid ($HClO_4$) in acetonitrile (MeCN).[6,7] An acid-stable NADH analogue, 10-methyl-9,10-dihydroacridine ($AcrH_2$) is used as a reductant for the acid catalysed reactions, since NADH and ordinary NADH model compounds are known to decompose in the presence of acid.[8] Here we report that efficient multi-electron (four-electron or six-electron) reduction of nitrobenzene derivatives by $AcrH_2$ also takes place in the presence of $HClO_4$ in MeCN. We have also studied acid catalysed photoinduced electron transfer reactions from the excited state of $[Ru(bpy)_3]^{2+}$ (bpy = 2,2′-bipyridine) to the same series of nitrobenzene derivatives as used for the multi-electron reduction by $AcrH_2$. Comparison of the acid catalysed two-electron and multi-electron reduction of substrates by an NADH analogue with the corresponding acid catalysed photoinduced electron transfer reactions of the same substrates, combined with the detailed kinetic studies on these reactions, will clarify the role of the acid catalysed electron transfer processes in the multi-electron reductions of these substrates by an NADH analogue.

Experimental

Materials.—10-Methyl-9,10-dihydroacridine ($AcrH_2$) was prepared from 10-methylacridinium iodide ($AcrH^+I^-$) by reduction with $NaBH_4$ in methanol, and purified by recrystallization from ethanol.[9] The dideuteriated compound, [9,9′-$^2H_2$]-10-methyl-9,10-dihydroacridine ($AcrD_2$), was prepared from 10-methylacridone by reduction with $LiAlD_4$,[10] which was obtained from Aldrich. Nitrosobenzene and nitrobenzene derivatives (nitrobenzene, *p*-nitrobenzyl bromide, *p*-nitrobenzyl alcohol, *o*-nitrotoluene, *m*-nitrotoluene, *p*-nitrotoluene, *p*-chloronitrobenzene, *p*-ethylnitrobenzene, *p*-cyanonitrobenzene) and the corresponding aniline derivatives were also obtained commercially and purified by the standard methods.[11] Phenylhydroxylamine was prepared by the standard method[12] of reduction of nitrobenzene with ammonium chloride and zinc dust. *p*-Aminophenethyl alcohol was prepared by the reduction of *p*-aminoacetophenone by $AcrH_2$ in the presence of perchloric acid in acetonitrile. **For safety reasons**, perchloric acid containing 30% water, obtained from Wako Pure Chemicals, was used in this study. Tris(2,2′-bipyridine)-ruthenium(II) dichloride hexahydrate, $[Ru(bpy)_3]Cl_2{\cdot}6H_2O$ was prepared and purified by the literature procedure.[13] Acetonitrile or [$^2H_3$]acetonitrile (CD_3CN) used as a solvent was purified and thoroughly dried with calcium hydride by the standard procedure.[11]

Reaction Procedure.—Typically, $AcrH_2$ (90 μmol) was added to an NMR tube containing a deaerated acetonitrile (CD_3CN) solution (0.6 cm^3) of nitrobenzene derivative (30 μmol) and $HClO_4$ (180 μmol). After the reactant solution in the NMR tube had been deaerated again by bubbling through with argon gas, the NMR tube was immersed in a water bath which was thermostatted at 313 K. The products were identified by comparing the ^1H NMR spectra of the products with those of authentic samples of $AcrH^+$ and reduced products. The deuterium incorporation into products was also determined from the ^1H NMR spectra. The ^1H NMR spectra of chemically induced dynamic nuclear polarization (CIDNP) were measured upon mixing nitrobenzene derivatives (4.0×10^{-2} mol dm^{-3}) with $AcrH_2$ (0.15 mol dm^{-3}) in the presence of $HClO_4$ (2.0 mol dm^{-3}) in CD_3CN at 335 K. The ^1H NMR measurements were carried out using a Japan Electron Optics JNM-PS-100 ^1H NMR spectrometer (100 MHz).

Kinetic Measurements.—The rates of the acid catalysed reduction of nitrobenzene derivatives by $AcrH_2$ were monitored by measuring the rise of the absorbance due to $AcrH^+$ (λ_{max} = 358 nm, $\varepsilon = 1.8 \times 10^4$ dm^3 mol^{-1} cm^{-1}), using a JASCO UVDEC-220B spectrophotometer. Fast reactions of $AcrH_2$ with nitrosobenzene in the presence of $HClO_4$ in MeCN with half-lives shorter than 10 s were determined using a Union RA-103 stopped-flow spectrophotometer. Kinetic measurements were normally carried out under conditions in which the concentrations of substrates and $HClO_4$ were maintained at

Table 1 Acid catalysed reductions of nitrosobenzene and nitrobenzene derivatives by $AcrH_2$ in the presence of $HClO_4$ in acetonitrile

Substrate/mol dm^{-3}	$AcrH_2$/mol dm^{-3}	T/K	t/min	Product yield (%)
$PhNO_2$ (0.05)[a]	0.10	313	36	PhNHOH (90)[b]
PhNO (0.10)[c]	0.15	298	*d*	PhNHOH (100)
p-$MeC_6H_4NO_2$ (0.04)[a]	0.20	338	15	*p*-$MeC_6H_4NH_2$ (82)
m-$C_6H_4NO_2$ (0.04)[a]	0.20	338	15	*m*-$MeC_6H_4NH_2$ (16)
p-$EtC_6H_4NO_2$ (0.04)[a]	0.10	333	50	*p*-$EtC_6H_4NH_2$ (60)[e]
p-$NO_2C_6H_4CH_2Br$ (0.04)[a]	0.20	338	7	*p*-$NH_2C_6H_4CH_2Br$ (50)

[a] In the presence of 2.0 mol dm^{-3} $HClO_4$. [b] The PhNHOH decomposed slowly in a prolonged reaction time, but no azoxybenzene or hydrazobenzene was formed under the present experimental conditions. [c] In the presence of 0.30 mol dm^{-3} $HClO_4$. [d] The reaction was completed upon mixing the reactants. [e] Another product was *p*-$NH_2C_6H_4CH(OH)Me$ (40%) which corresponds to a rearranged product of *p*-EtC_6H_4NHOH.

Table 2 Observed rate constant (k_{obs}) and the primary kinetic isotope effects (k_H/k_D) for the acid catalysed reduction of nitrosobenzene in the presence of $HClO_4$ in deaerated MeCN at 298 K

$[HClO_4]$/mol dm^{-3}	k_{obs}[a]/dm^3 mol^{-1} s^{-1}	k_H/k_D[a]
1.0×10^{-2}	2.3×10^3	1.0
5.0×10^{-3}	2.5×10^3	1.0
2.5×10^{-3}	2.4×10^3	1.0
1.3×10^{-3}	2.4×10^3	1.0

[a] The experimental errors are within ± 10%.

greater than ten-fold excess of the concentration of $AcrH_2$. All the rate constants were determined by least-squares curve fit according to the determined kinetic formulations, using a micro-computer.

Luminescence Quenching.—Quenching experiments on the $[Ru(bpy)_3]^{2+}$ * luminescence were carried out on a Hitachi 650-10S fluorescence spectrophotometer. The excitation and monitoring wavelengths, which are beyond the quencher absorption, were those corresponding to the absorption and emission maxima of $[Ru(bpy)_3]^{2+}$ (452 and 608 nm, respectively). The MeCN solution of $[Ru(bpy)_3]^{2+}$ was deaerated prior to measurements. It was confirmed that the luminescence intensity was unaffected by the presence of $HClO_4$ up to concentrations of 2.0 mol dm^{-3}.[14] Relative emission intensities were measured for acetonitrile solutions of $[Ru(bpy)_3]^{2+}$ (1.0×10^{-5} mol dm^{-3}) with a quencher at various concentrations. There was no change in the shape, but there was a change in the intensity of the emission spectrum by the addition of a quencher. The Stern–Volmer relationship [eqn. (1)] was obtained between the ratio of the emission intensities in

$$I_0/I = 1 + k_{et}\tau[Q] \quad (1)$$

the absence and presence of a quencher (I_0/I) and the quencher concentration [Q]. The rate constant (k_{et}) of acid catalysed electron transfer from $[Ru(bpy)_3]^{2+}$ * to nitrobenzene derivatives was obtained from the slope of the plot of I_0/I *versus* [Q] and the emission lifetime τ of $[Ru(bpy)_3]^{2+}$ * (τ 850 ns).[15]

Results

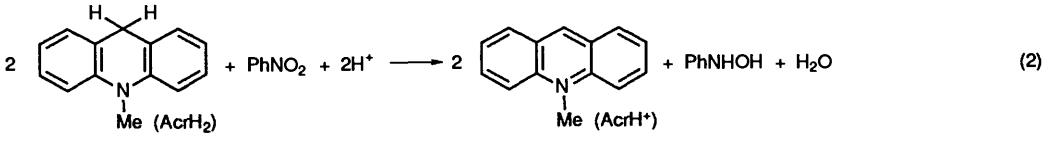
Acid Catalysed Multi-electron Reduction of Nitrobenzene Derivatives by $AcrH_2$.—Nitrobenzene can be reduced by $AcrH_2$ in the presence of $HClO_4$ in CD_3CN to yield the four-electron reduction product, phenylhydroxylamine [eqn. (2)]. No reduction of nitrobenzene by $AcrH_2$ has been observed in the absence of $HClO_4$. Phenylhydroxylamine decomposed in the presence of $HClO_4$ with prolonged reaction time. The maximum yield of phenylhydroxylamine is listed in Table 1. Phenylhydroxylamine is also formed by the stoichiometric reduction of nitrosobenzene by $AcrH_2$ in the presence of $HClO_4$ (Table 1), eqn. (3).

$$AcrH_2 + PhNO + H^+ \xrightarrow{k_{obs}} AcrH^+ + PhNHOH \quad (3)$$

The rate of the acid catalysed reduction of nitrosobenzene by $AcrH_2$ is much faster than that of nitrobenzene and therefore determination of the rate required a stopped-flow technique (see Experimental section). The rate of formation of $AcrH^+$ obeyed pseudo first-order kinetics under conditions in which the concentrations of PhNO were in a large excess of the $AcrH_2$ concentration. The pseudo first-order rate constants were proportional to the PhNO concentration and the observed second-order rate constants (k_{obs}) of the acid catalysed reduction of PhNO by $AcrH_2$ and $AcrD_2$ are listed in Table 2. The k_{obs} value is independent of the $HClO_4$ concentration (Table 2). The primary kinetic isotope effects (k_H/k_D) were also examined by replacing $AcrH_2$ with the 9,9′-dideuteriated analogue ($AcrD_2$). The k_H/k_D values were determined from the ratios of the rate constants of $AcrH_2$ to those of $AcrD_2$ when the secondary kinetic isotope effects are assumed to be unity. No kinetic isotope effect has been observed in this case, $k_H/k_D = 1$, as shown in Table 2.

When *p*-nitrotoluene is used as the substrate, the acid catalysed reduction by $AcrH_2$ yields the six-electron reduction product, *p*-methylaniline, as shown in Table 1. The reduction of *m*-nitrotoluene, *p*-ethylnitrobenzene and *p*-nitrobenzyl bromide also gives the corresponding six-electron reduction products, *m*-methylaniline, *p*-ethylaniline and *p*-aminobenzyl bromide, respectively. In the case of *p*-ethylnitrobenzene, *p*-aminophenethyl alcohol (which corresponds to the rearranged product of *p*-ethylphenylhydroxylamine) is also formed (Table 1).

When ^1H NMR spectra were measured at 335 K upon mixing a CD_3CN solution of $AcrH_2$ (0.15 mol dm^{-3}) containing $HClO_4$ (2.0 mol dm^{-3}) with various nitrobenzene derivatives (4.0×10^{-2} mol dm^{-3}), the emission signals due to the *ortho* protons of nitrobenzene derivatives are observed in the first scan (250 s), as shown in Fig. 1. The reaction rates at 338 K were fast and each reaction was completed in several scans. As the temperature was lowered, the rates were slowed



(2)

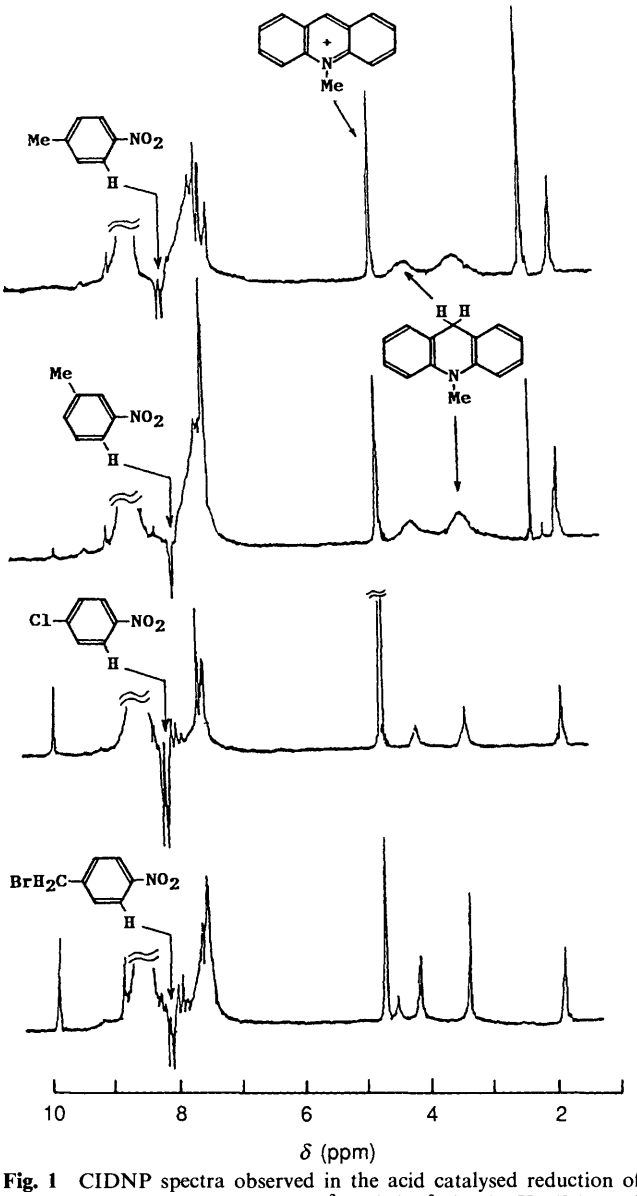


Fig. 1 CIDNP spectra observed in the acid catalysed reduction of nitrobenzene derivatives (4.0×10^{-2} mol dm^{-3}) by $AcrH_2$ (0.15 mol dm^{-3}) in the presence of 2.0 mol dm^{-3} $HClO_4$ (70%) in CD_3CN at 338 K

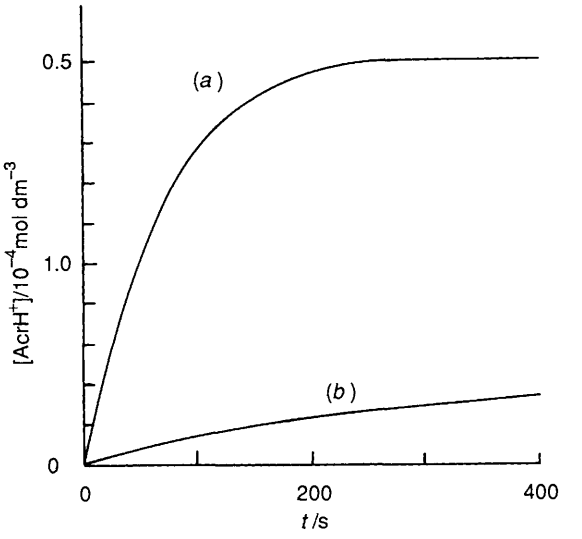


Fig. 2 Time dependence for the formation of $AcrH^+$ in the acid catalysed reduction of p-$MeC_6H_4NO_2$ (5.0×10^{-4} mol dm^{-3}) by $AcrH_2$ (1.0×10^{-4} mol dm^{-3}) in the presence of $HClO_4$ (2.0 mol dm^{-3}) in (*a*) deaerated MeCN and (*b*) aerated MeCN at 298 K

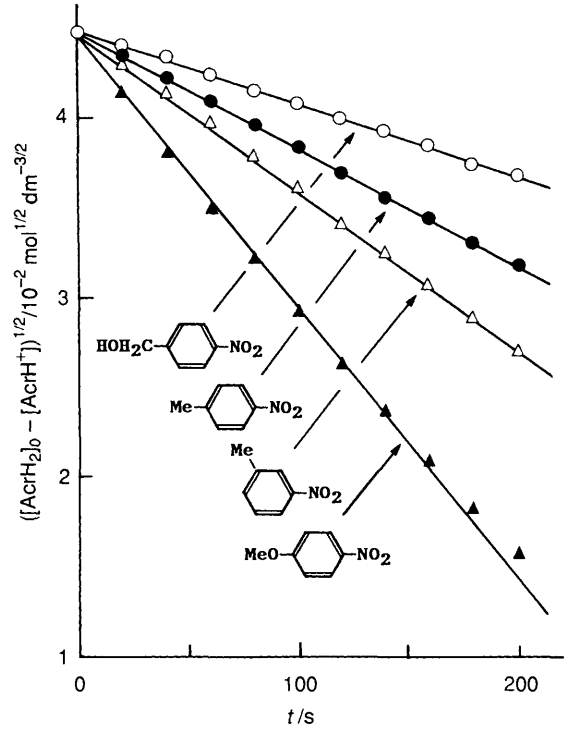


Fig. 3 Plots of $([AcrH_2]_0-[AcrH^+])^{\frac{1}{2}}$ *versus* time for the acid catalysed reduction of nitrobenzene derivatives (5.0×10^{-3} mol dm^{-3}) by $AcrH_2$ in the presence of $HClO_4$ (2.0 mol dm^{-3}) in MeCN at 298 K

down, and the emission intensities decreased. No emission signals have been observed in the reactions at 298 K. On the other hand, the absorption signals due to $AcrH_2$ exhibit significant broadening when the emission signals are observed (Fig. 1).

The time dependence of formation of the oxidized product ($AcrH^+$) in the absence and presence of oxygen is shown in Fig. 2, where the reaction is strongly inhibited by the presence of dioxygen. The kinetic behaviour in the absence of oxygen, Fig. 2, appears to be different from ordinary pseudo first-order kinetics. In fact, plots of $([AcrH_2]_0 - [AcrH^+])^{\frac{1}{2}}$ *versus* reaction time for the acid catalysed reduction of various nitrobenzene derivatives give good linear correlations, as shown in Fig. 3, where $[AcrH_2]_0$ is the initial concentration of $AcrH_2$. Such linear correlations indicate that the rate of formation of $AcrH^+$ is proportional to $([AcrH_2]_0 - [AcrH^+])^{\frac{1}{2}}$, eqn. (4),

$$d[AcrH^+]/dt = k_{obs}([AcrH_2]_0 - [AcrH^+])^{\frac{1}{2}} \quad (4)$$

from which we can derive eqn. (5). Thus, the rate constants k_{obs}

$$([AcrH_2]_0 - [AcrH^+])^{\frac{1}{2}} = [AcrH_2]_0 - k_{obs}t/2 \quad (5)$$

[units dm$^{\frac{3}{2}}$ mol$^{-\frac{1}{2}}$ s^{-1}] are obtained from the slopes of the linear correlations in Fig. 3. The k_{obs} values increase linearly with an increase in the $HClO_4$ concentration as shown in Fig. 4. The k_{obs} values for the reduction of various nitrobenzene derivatives (5.0×10^{-3} mol dm^{-3}) by $AcrH_2$ in the presence of 2.0 mol dm^{-3} $HClO_4$ in MeCN at 298 K are listed in Table 3.

The dependence of k_{obs} on the concentration of $PhNO_2$ was also examined under conditions such that 2.0×10^{-4} mol dm^{-3} $< [PhNO_2] < 5.0 \times 10^{-3}$ mol dm^{-3}. The k_{obs} value was also proportional to $[PhNO_2]^{\frac{1}{2}}$. Addition of H_2O to the $AcrH_2$–$PhNO_2$ system in the presence of $HClO_4$ resulted in a significant decrease in the k_{obs} value, since the acid strength of

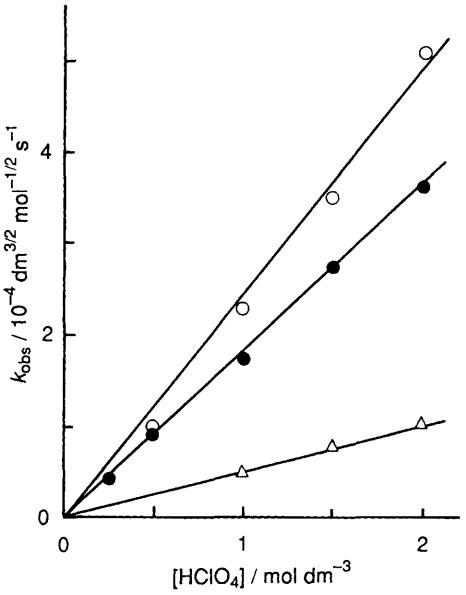


Fig. 4 Dependence of k_{obs} on [$HClO_4$] for the acid catalysed reduction of *p*-$MeC_6H_4NO_2$ (○), $PhNO_2$ (●), and *p*-$NO_2C_6H_4CH_2Br$ (△) by $AcrH_2$ in MeCN at 298 K

Table 3 Observed one-half-order rate constants (k_{obs}) and the primary kinetic isotope effects (k_H/k_D) for the acid catalysed reduction of nitrobenzene derivatives (1.0×10^{-3} mol dm^{-3}) by $AcrH_2$ and $AcrD_2$ in the presence of $HClO_4$ (2.0 mol dm^{-3}) in MeCN at 298 K

Substrate	k_{obs}[a]/dm$^{\frac{3}{2}}$ mol$^{-\frac{1}{2}}$ s^{-1}	k_H/k_D[a]
p-$MeOC_6H_4NO_2$	2.9×10^{-4}	5.8
p-$EtC_6H_4NO_2$	1.8×10^{-4}	*b*
m-$MeC_6H_4NO_2$	1.7×10^{-4}	7.3
p-$MeC_6H_4NO_2$	1.3×10^{-4}	6.0
$PhNO_2$	8.5×10^{-5}	6.8
p-$NO_2C_6H_4CH_2OH$	7.9×10^{-5}	7.8
p-$NO_2C_6H_4CH_2Br$	2.9×10^{-5}	5.2
p-$ClC_6H_4NO_2$	2.6×10^{-5}	6.9
p-$NO_2C_6H_4CO_2Me$	2.5×10^{-6}	*b*
p-$CNC_6H_4NO_2$	*c*	*c*

[a] The experimental errors are within ±10%. [b] Not determined. [c] Too slow to be determined accurately.

$HClO_4$ in MeCN may decrease with an increase in the H_2O concentration. The primary kinetic isotope effects (k_H/k_D) for the acid catalysed reduction of nitrobenzene derivatives were also determined by using $AcrD_2$ and the k_H/k_D values are listed together in Table 3. In contrast with the case of the reduction of nitrosobenzene (Table 2), the large k_H/k_D values are obtained for the reduction of nitrobenzene derivatives (Table 3).

Acid Catalysed Photoinduced Electron Transfer from [Ru(bpy)$_3$]$^{2+}$* *to Nitrobenzene Derivatives.*—Nitrobenzene derivatives with electron-withdrawing substituents (*e.g.* *p*-$NO_2C_6H_4NO_2$) are known to quench the emission of [Ru(bpy)$_3$]$^{2+}$* (* denotes the excited state) by electron transfer [eqn. (6)].[15]

$$[Ru(bpy)_3]^{2+}* + p\text{-}NO_2C_6H_4NO_2 \longrightarrow [Ru(bpy)_3]^{3+} + p\text{-}NO_2C_6H_4NO_2^{\bullet -} \quad (6)$$

However, little quenching has been observed by nitrobenzene or nitrobenzene derivatives with electron-donating substituents. The presence of $HClO_4$ significantly accelerates the electron transfer from [Ru(bpy)$_3$]$^{2+}$* to nitrobenzene, as is the case for the acid catalysed electron transfer from [Ru(bpy)$_3$]$^{2+}$* to

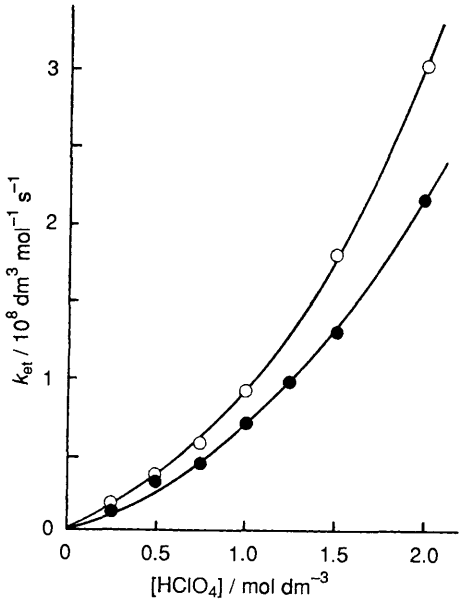


Fig. 5 Dependence of k_{et} on [$HClO_4$] for the acid catalysed electron transfer from [Ru(bpy)$_3$]$^{2+}$* to *p*-$MeC_6H_4NO_2$ (○) and *p*-$EtC_6H_4NO_2$ (●) in MeCN at 298 K

carbonyl compounds.[3,14] The k_{et} values for the photoinduced electron transfer from [Ru(bpy)$_3$]$^{2+}$* to nitrobenzene and *p*-nitrotoluene increase parabolically with an increase in the $HClO_4$ concentration as shown in Fig. 5. Such a parabolic dependence of the rate of electron transfer on the $HClO_4$ concentration has also been reported for the acid catalysed electron transfer from the *cis*-diethylcobalt(III) complex, *cis*-[$Et_2Co(bpy)_2$]$^+$, to *p*-benzoquinone derivatives (Q) in H_2O–EtOH (5:1 v/v) under highly acidic conditions such that two protons are involved for the one-electron reduction of Q to yield hydroquinone radical cation ($QH_2^{\bullet +}$), eqn. (7).[16] Thus,

$$cis\text{-}[Et_2Co(bpy)_2]^+ + Q + 2H^+ \longrightarrow cis\text{-}[Et_2Co(bpy)_2]^{2+} + QH_2^{\bullet +} \quad (7)$$

the acid catalysed electron transfer from [Ru(bpy)$_3$]$^{2+}$* to nitrobenzene derivatives (X–$C_6H_4NO_2$) may result in the one-electron reduction associated with two protons to yield X–$C_6H_4NO_2H_2^{\bullet +}$ [eqn. (8)]. The k_{et} values of various nitro-

$$[Ru(bpy)_3]^{2+}* + X\text{–}C_6H_4NO_2 + 2H^+ \longrightarrow [Ru(bpy)_3]^{3+} + X\text{–}C_6H_4NO_2H_2^{\bullet +} \quad (8)$$

benzene derivatives in the presence of 2.0 mol dm^{-3} $HClO_4$ are listed in Table 4, where the k_{et} values of X–$C_6H_4NO_2$ with electron-withdrawing substituents (X = *p*-CN, *p*-CO_2Me) are larger than those with the other substituents. Such reactivities of X–$C_6H_4NO_2$ in the acid catalysed electron-transfer reactions are opposite to those in the acid catalysed reduction by $AcrH_2$ in Table 2. Addition of H_2O to the [Ru(bpy)$_3$]$^{2+}$*–X–$C_6H_4NO_2$ system in the presence of $HClO_4$ in MeCN, however, resulted in a significant decrease in the k_{et} value as observed in the acid catalysed reduction of X–$C_6H_4NO_2$ by $AcrH_2$ (*vide supra*).

Discussion

The observation of CIDNP spectra (Fig. 1), the inhibiting effect of oxygen (Fig. 2), and the one-half order dependence of the rate on the $AcrH_2$ concentration (Fig. 3) indicate that the acid catalysed reduction of nitrobenzene derivatives by $AcrH_2$ proceeds *via* radical-chain reactions. The large k_H/k_D values

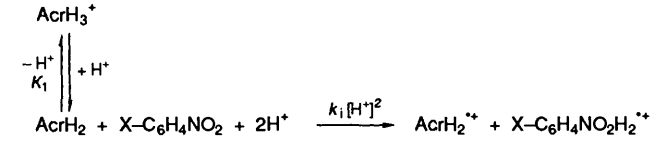
Table 4 Rate constants (k_{et}) of the acid catalysed electron transfer from $[Ru(bpy)_3]^{2+}$* to nitrobenzene derivatives in the presence of $HClO_4$ (2.0 mol dm^{-3}) in MeCN at 298 K

Substrate	k_{et}[a]/dm^3 mol^{-1} s^{-1}
p-$CNC_6H_4NO_2$	2.5×10^9
p-$NO_2C_6H_4CO_2Me$	2.0×10^9
p-$NO_2C_6H_4CH_2Br$	5.3×10^8
p-$NO_2C_6H_4CH_2OH$	4.0×10^8
p-$MeC_6H_4NO_2$	3.1×10^8
$PhNO_2$	3.0×10^8
p-$MeOC_6H_4NO_2$	3.0×10^8
p-$ClC_6H_4NO_2$	2.9×10^8
m-$MeC_6H_4NO_2$	2.7×10^8
p-$EtC_6H_4NO_2$	2.2×10^8

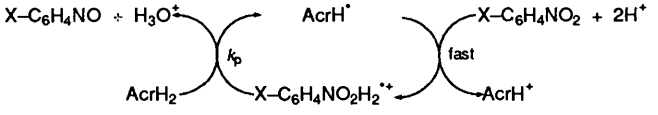
[a] The experimental errors are within ±10%.

observed for the acid catalysed reduction of nitrobenzene derivatives by $AcrH_2$ (Table 2) demonstrate the involvement of a hydrogen transfer process from $AcrH_2$ in the rate-determining chain propagation step. The radical chain mechanism that can account for all the experimental results may be summarized as shown in Scheme 1.

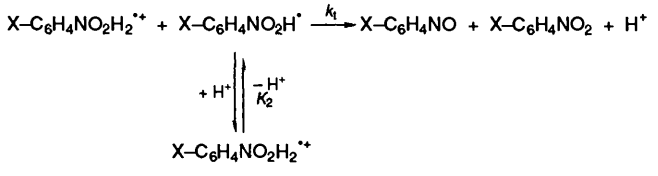
Initiation



Propagation



Termination



Scheme 1

The initiation step may be acid catalysed electron transfer from $AcrH_2$ to $X\text{-}C_6H_4NO_2$ (Scheme 1), in which two protons are incorporated into the reduced product to yield $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ as demonstrated for the acid catalysed photoinduced electron transfer from $[Ru(bpy)_3]^{2+}$* to $X\text{-}C_6H_4NO_2$ [eqn. (8)]. The rate of the initiation step is thus given by eqn. (9),

$$R_i = k_i[H^+]^2[AcrH_2][X\text{-}C_6H_4NO_2] \quad (9)$$

where $k_i[H^+]^2$ corresponds to acid catalysed electron transfer from $AcrH_2$ to $X\text{-}C_6H_4NO_2$. In the presence of $HClO_4$, however, $AcrH_2$ is known to be protonated in MeCN and only the unprotonated $AcrH_2$ is active for the electron transfer reactions (Scheme 1).[6,7] In such a case R_i may be rewritten by eqn. (10), where $[AcrH_2]_t$ is the total concentration of $AcrH_2$ and $AcrH_3^+$.

$$R_i = k_iK_1[H^+][AcrH_2]_t[X\text{-}C_6H_4NO_2] \quad (10)$$

The propagation step may consist of two redox reactions; one is hydrogen transfer from $AcrH_2$ to $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ to give AcrH• and $X\text{-}C_6H_4NO$ after dehydration, and the other is the acid catalysed electron transfer from AcrH• to $X\text{-}C_6H_4NO_2$ to yield $AcrH^+$ accompanied by regeneration of $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ (Scheme 1). The observation of large primary kinetic isotope effects (Table 2) indicates that hydrogen transfer from $AcrH_2$ to $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ is the rate-determining process in the chain propagation step. In such a case the most efficient termination step may be reaction of $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ with the deprotonated radical, $X\text{-}C_6H_4NO_2H^{\bullet}$ to yield $X\text{-}C_6H_4NO$ and $X\text{-}C_6H_4NO_2$ (Scheme 1), since the disproportionation of radical cations ($X\text{-}C_6H_4NO_2H_2^{\bullet+}$) may be slow because of coulombic repulsion and that of neutral radicals ($X\text{-}C_6H_4NO_2H^{\bullet}$) may also be slow because of the favourable protonation equilibrium toward $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ (*vide supra*).

Under steady-state conditions the rate of initiation (R_i) is equal to the rate of termination, *i.e.* eqn. (11) from which

$$k_iK_1[H^+][AcrH_2]_t[X\text{-}C_6H_4NO_2] = 2k_tK_2[H^+]^{-1}[X\text{-}C_6H_4NO_2H_2^{\bullet+}]^2 \quad (11)$$

is derived the steady state concentration of $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ as shown in eqn. (12), where $\alpha = (k_iK_1/2k_tK_2)^{\frac{1}{2}}$. Since the steady-state concentration of $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ [eqn. (12)] is

$$[X\text{-}C_6H_4NO_2H_2^{\bullet+}] = \alpha[H^+][AcrH_2]_t^{\frac{1}{2}}[X\text{-}C_6H_4NO_2]^{\frac{1}{2}} \quad (12)$$

proportional to the observed rate (Figs. 3 and 4), the rate-determining hydrogen transfer from $AcrH_2$ to $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ (Scheme 1) may proceed *via* formation of the strong charge-transfer complex [eqn. (13)]. In such a case the overall

$$AcrH_2 + X\text{-}C_6H_4NO_2H_2^{\bullet+} \rightleftharpoons (AcrH_2X\text{-}C_6H_4NO_2H_2^{\bullet+}) \xrightarrow{k_p} AcrH^{\bullet} + X\text{-}C_6H_4NO + H_2O^+ \quad (13)$$

rate is given by eqn. (14), which agrees with the experimental observations (*vide supra*). Eqn. (14) contains various elementary

$$d[AcrH^+]/dt = k_p\alpha[H^+][AcrH_2]_t^{\frac{1}{2}}[X\text{-}C_6H_4NO_2]^{\frac{1}{2}} \quad (14)$$

reactions in Scheme 1, the acid catalysed electron transfer (k_i), the termination step (k_t), the hydrogen transfer reaction (k_p), and the protonation equilibria (K_1 and K_2). This may be the reason why the k_{obs} values in Table 3 show no apparent correlation with the k_{et} values of the acid catalysed photoinduced electron transfer from $[Ru(bpy)_3]^{2+}$* to the corresponding nitrobenzene derivatives in Table 4. Nonetheless, the initiation step of acid catalysed electron transfer plays an important role in determining the overall reactivity as demonstrated by the fact that the addition of H_2O retards the reaction significantly, since the acid catalysed electron transfer step is slowed down with an increase in the H_2O concentration (*vide supra*). The large primary kinetic isotope effects (k_H/k_D) in Table 3 may well be ascribed to those in the hydrogen transfer from $AcrH_2$ to $X\text{-}C_6H_4NO_2H_2^{\bullet+}$ [k_p, eqn. (13)]. The inhibition effect of dioxygen (Fig. 2) is also accounted for by the efficient trap of one of the chain carrier radicals, *i.e.* AcrH• by dioxygen, as reported previously.[16,17] Such strong oxygen inhibition is in fact recognized as the most unique characteristic of nitroreductase.[18]

The CIDNP results in Fig. 1 also indicate that $X\text{–}C_6H_4NO_2H_2^{\bullet+}$ is indeed a chain carrier radical (*vide infra*). The polarization of nitrobenzene derivatives in the CIDNP spectra (Fig. 1) observed at a high temperature (338 K) may be ascribed to the alternative termination step [eqn. (15)] in which * denotes the nuclear polarization. As the temperature is raised, the rate of initiation to yield $AcrH_2^{\bullet+}$ becomes faster, when the termination reaction of $X\text{–}C_6H_4NO_2H_2^{\bullet+}$ (or $X\text{–}C_6H_4NO_2H^{\bullet}$) with $AcrH_2^{\bullet+}$ [eqn. (15)] may also take place together with the disproportionation reaction of $X\text{–}C_6H_4NO_2H_2^{\bullet+}$ in Scheme 1. The broadening of the ^1H NMR signals due to $AcrH_2$ in Fig. 1 also indicates the presence of $AcrH_2^{\bullet+}$, since the broadening may be caused by the exchange reaction between $AcrH_2^{\bullet+}$ and $AcrH_2$ [eqn. (16)]. According to eqn. (15) the radical pair is

$$\overline{AcrH_2^{\bullet+} + X\text{–}C_6H_4NO_2H^{\bullet}}^{F} \longrightarrow AcrH_2^{*} + X\text{–}C_6H_4NO_2^{*} + H^+ \quad (15)$$

$$AcrH_2^{\bullet+} + AcrH_2 \rightleftharpoons AcrH_2 + AcrH_2^{\bullet+} \quad (16)$$

formed by the encounter of free radicals (F) of $AcrH_2^{\bullet+}$ and $X\text{–}C_6H_4NO_2H^{\bullet}$ and back electron transfer from $X\text{–}C_6H_4NO_2H^{\bullet}$ to $AcrH_2^{\bullet+}$ regenerates the reactant pair. The g value of $X\text{–}C_6H_4NO_2H^{\bullet}$ (2.0048)[19] is larger than that of $AcrH_2^{+\bullet}$ (2.0027)[20] Thus, we would expect polarization of the *ortho* protons of $X\text{–}C_6H_4NO_2$ that have negative hyperfine constants[19] according to Kaptein's rule[21] ($\Gamma_{NE} = + + + - = - = E$), which is in fact observed in Fig. 1. The line broadening of the $AcrH_2$ signals due to the exchange reaction [eqn. (16)], however, obscures any possible polarization of the $AcrH_2$ protons.

The two-electron reduction product, $X\text{–}C_6H_4NO$, may be further reduced by $AcrH_2$ *via* acid catalysed electron transfer from $AcrH_2$ to $X\text{–}C_6H_4NO$, followed by hydrogen transfer from $AcrH_2^{\bullet+}$ to $X\text{–}C_6H_4NOH^{\bullet}$, yielding the corresponding four-electron reduction product, $X\text{–}C_6H_4NHOH$, as shown in Scheme 2. In this case, the acid catalysed electron transfer may

$$AcrH_2 + X\text{–}C_6H_4NO + H^+ \longrightarrow (AcrH_2^{\bullet+}\ X\text{–}C_6H_4NOH^{\bullet}) \xrightarrow{fast} AcrH^+ + X\text{–}C_6H_4NHOH$$

Scheme 2

be the rate-determining step, since no primary kinetic isotope effect has been observed as shown in Table 2. Nitrosobenzene is known to be a much better oxidant than nitrobenzene.[22] In fact, the acid catalysed reduction of nitrosobenzene, which is the two-reduction product of nitrobenzene, is much faster than the acid catalysed reduction of nitrobenzene by $AcrH_2$ (compare Tables 2 and 3).

It is well known that phenylhydroxylamine readily rearranges in the presence of acid to give *p*-aminophenol.[23] This may be the reason why no further reduction of phenylhydroxylamine has occurred in the present case (Table 1). When an appropriate substituent is introduced at the *para* position, however, the four-electron reduction product, $X\text{–}C_6H_4NHOH$ (*e.g.* X = Me), is further reduced by $AcrH_2$ to yield the corresponding six-electron reduction product, $X\text{–}C_6H_4NH_2$ (Table 1).

References

1 U. Eisner and J. Kuthan, *Chem. Rev.*, 1972, **72**, 1; D. M. Stout and A. I. Meyer, *Chem. Rev.*, 1982, **82**, 223; R. M. Kellogg, *Top. Curr. Chem.*, 1982, **101**, 111; R. J. Kill and D. A. Widdowson, in *Bioorganic Chemistry*, ed. E. E. van Tamelen, vol. IV, Academic Press, New York, 1978, p. 239.
2 S. Fukuzumi, S. Mochizuki and T. Tanaka, *J. Chem. Soc., Chem. Commun.*, 1989, 391; S. Fukuzumi, S. Mochizuki and T. Tanaka, *Inorg. Chem.*, 1990, **29**, 653.
3 S. Fukuzumi and T. Tanaka, in *Photoinduced Electron Transfer*, eds. M. A. Fox and M. Chanon, Part C, Elsevier, Amsterdam, 1988, ch. 10, p. 636.
4 M. Dixon, E. C. Webb, C. J. R. Thorne and K. F. Tipton, *Enzymes*, 3rd edn., Academic Press, New York, 1979, p. 684.
5 D. C. Dittmer and J. M. Kolyer, *J. Org. Chem.*, 1962, **27**, 56; E. A. Braude, J. Hannah and R. Linstead, *J. Chem. Soc.*, 1960, 3257.
6 S. Fukuzumi, S. Mochizuki and T. Tanaka, *J. Am. Chem. Soc.*, 1989, **111**, 1497; S. Fukuzumi, M. Chiba and T. Tanaka, *Chem. Lett.*, 1989, 31; M. Ishikawa and S. Fukuzumi, *J. Chem. Soc., Chem. Commun.*, 1990, 1353.
7 S. Fukuzumi, M. Ishikawa and T. Tanaka, *J. Chem. Soc., Chem. Commun.*, 1985, 1069; *Tetrahedron*, 1986, **42**, 1021.
8 C. C. Johnston, J. L. Gardner, C. H. Suelter and D. E. Metzler, *Biochemistry*, 1963, **2**, 689; P. van Eikeren, D. L. Grier and J. Eliason, *J. Am. Chem. Soc.*, 1979, **101**, 7406; E. Skibo and T. C. Bruice, *J. Am. Chem. Soc.*, 1983, **105**, 3316.
9 A. K. Colter, G. Saito and F. Sharom, *Can. J. Chem.*, 1977, **55**, 2741.
10 P. Karrer, L. Szabo, H. J. V. Krishna and R. Schwyzer, *Helv. Chim. Acta*, 1950, **33**, 294.
11 D. D. Perrin, W. L. F. Armarego and D. R. Perrin, *Purification of Laboratory Chemicals*, Pergamon Press, New York, 1966.
12 A. I. Vogel, *Practical Organic Chemistry*, 2nd edn., Longman, London, 1954, p. 602.
13 F. H. Burstall, *J. Chem. Soc.*, 1936, 173.
14 S. Fukuzumi, K. Ishikawa, K. Hironaka and T. Tanaka, *J. Chem. Soc., Perkin Trans. 2*, 1987, 751.
15 C. R. Boch, J. A. Connor, A. R. Gutierrez, T. J. Meyer, D. G. Whitten, B. P. Sullivan and J. K. Nagle, *J. Am. Chem. Soc.*, 1979, **101**, 4815.
16 S. Fukuzumi, M. Ishikawa and T. Tanaka, *J. Chem. Soc., Perkin Trans. 2*, 1989, 1037.
17 S. Fukuzumi, T. Kitano and M. Mochida, *J. Am. Chem. Soc.*, 1990, **112**, 3246.
18 R. P. Mason, in *Free Radicals in Biology*, ed. W. A. Pryor, Academic Press, New York, 1982, vol. V, p. 161.
19 N. Levy and M. D. Cohen, *J. Chem. Soc., Perkin Trans. 2*, 1979, 553.
20 S. Fukuzumi and T. Kitano, *Chem. Lett.*, 1990, 1275.
21 R. Kaptein, *Chem. Commun.*, 1971, 732.
22 W. H. Smith and A. J. Bard, *J. Am. Chem. Soc.*, 1975, **97**, 5203.
23 H. J. Shine, *Aromatic Rearrangements*, Elsevier, Amsterdam, 1967, pp. 124–271.

Paper 1/02138I
Received 7*th May* 1991
Accepted 31*st May* 1991