Effects of Base on Oxidation of an NADH Model Compound by Iron(III) Complexes and Tetracyanoethylene

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Effects of base on both an electron-transfer reaction from an NADH model compound, 1-benzyl-1,4-dihydronicotinamide (BNAH) to $[Fe(N-N)_3]^{3+}$ (N–N = 2,2′-bipyridine and 1,10-phenanthroline) and a hydride transfer from BNAH to tetracyanoethylene (TCNE) in acetonitrile have been examined. The stoicheiometry of the electron transfer from BNAH to $[Fe(N-N)_3]^{3+}$ in the absence of a base indicates that BNAH is a one-electron donor. In the presence of a base, however, BNAH acts as an apparent two-electron donor, when the two-electron transfer proceeds *via* a multistep process; a fast one-electron transfer from BNAH to $[Fe(N-N)_3]^{3+}$ occurred, followed by the rate-determining deprotonation of $BNAH^{+\cdot}$ by base and the subsequent fast electron transfer from $BNA^\cdot$ to $[Fe(N-N)_3]^{3+}$. The rate constants for the proton transfer from $BNAH^{+\cdot}$ to a series of pyridine derivatives have been determined. In the reduction of TCNE by BNAH, BNAH appears to be a two-electron donor in both the absence and presence of a base. Rates of the reduction of TCNE by BNAH increased with increasing base concentration, suggesting the involvement of $BNAH^{+\cdot}$ as an intermediate in the hydride transfer from BNAH to TCNE. The kinetic analyses have led to the evaluation of the proton transfer rate constants for the deprotonation of $BNAH^{+\cdot}$ with various bases, which accord with those obtained from the electron-transfer reactions of BNAH with $[Fe(N-N)_3]^{3+}$ in the presence of bases. Based on the Brönsted plot of the proton transfer rate constants as well as the variation of the primary kinetic isotope effects k_H/k_D with the pK_a of the base, the pK_a value for $BNAH^{+\cdot}$ has been evaluated as 3.6 ± 0.4.

Although most reductions of substrates by NADH model compounds have generally been believed to occur *via* one-step hydride transfers (two-electron equivalent),[1] one-electron pathways which involve the radical cations of NADH model compounds as possible intermediates are receiving increased attention in both thermal [2–4] and photochemical [5,6] reactions. The existence of radical cations of NADH and of its model compounds has clearly been demonstrated by a recent CIDNP study on the NADH-flavin photoreactions, where the *g*-values and proton hyperfine coupling constants have been reported.[6] Thus, in photochemical reactions of NADH model compounds, where strong oxidants or reductants are involved, one-electron pathways seem to be predominant.[5,6] As far as the thermal reactions are concerned, however, one-electron pathways have remained uncertain,[7] despite extensive discussions on the mechanisms of hydride-transfer reactions of NADH model compounds.[2,3] On the other hand, there have been only a few studies of the mechanisms of thermal electron-transfer reactions of NADH model compounds with one-electron oxidants other than hydride acceptors.[8] Accordingly it seemed to be of interest to study electron-transfer reactions of NADH model compounds with one-electron oxidants for comparison with the hydride-transfer reactions with hydride acceptors.

In this study, we report a mechanistic comparison between electron-transfer reactions from an NADH model compound, 1-benzyl-1,4-dihydronicotinamide (BNAH), to strong one-electron oxidants $[Fe(N-N)_3]^{3+}$ (N–N = 2,2′-bipyridine and 1,10-phenanthroline) and a hydride transfer from BNAH to a hydride acceptor, tetracyanoethylene (TCNE), which is also a strong oxidant.[9] The radical cations of NADH model compounds formed by electron-transfer reactions are known to be deprotonated readily in the presence of a suitable base.[6,10] Thus, the effects of bases on both the electron transfer and hydride-transfer reactions will be compared with regard to the stoicheiometry, the kinetics, and the primary kinetic isotope effects.

Experimental

Materials.—1-Benzyl-1,4-dihydronicotinamide (BNAH) and [4-^{2}H]-1-benzyl-1,4-dihydronicotinamide were prepared by the literature method.[11] [4,4-$^2H_2$]-1-Benzyl-1,4-dihydronicotinamide was prepared from [4-$^2H_1$]BNAH by three cycles of oxidation with *p*-chloranil in dimethylformamide and reduction with dithionite in deuterium oxide.[12] The deuterium content of [4-$^2H_2$]BNAH was determined to be 96% by measurements on a Japan Electron Optics JNM-PS-100 ^{1}H n.m.r. spectrometer (100 MHz). The $[Fe(N-N)_3]X_3$ complexes (N–N = 2,2′-bipyridine, 1,10-phenanthroline; X = ClO_4, PF_6) were prepared as described elsewhere.[13] Tetracyanoethylene (TCNE) was purified by vacuum sublimation before use. The nine pyridine derivatives used as bases in this study were commercially available and purified by standard procedures.[14] Acetonitrile used as a solvent was purified and dried with calcium hydride by the standard method. 1-Benzylnicotinamidium hexafluorophosphate, $BNA^+PF_6^-$, was prepared by the addition of $NH_4^+PF_6^-$ to BNA^+Cl^- in H_2O (Found: C, 43.6; H, 3.8; N, 7.9. Calc. for $C_{13}H_{13}N_2OPF_6$: C, 43.6; H, 3.7; N, 7.8), δ_H (100 MHz; solvent CD_3CN; standard Me_4Si) 5.77 (2 H, s, NCH_2), 6.6—7.2 (2 H, br s, NH_2), 7.46 (5 H, m, Ph), 8.10 (1 H, t, 5-H), 8.72—8.83 (2 H, m, 4- and 6-H), and 9.15 (1 H, s, 2-H).

Kinetic Measurements.—Kinetic measurements were carried out using an Union RA-103 stopped flow spectrophotometer under deaerated conditions at 298 K. Rates of the electron-transfer reactions from BNAH to $[Fe(bpy)_3]^{3+}$ (bpy = 2,2′-bipyridine) and $[Fe(phen)_3]^{3+}$ (phen = 1,10-phenanthroline) in acetonitrile (MeCN) were followed by the increase in absorbance at $\lambda_{max.}$ 520 nm for $[Fe(bpy)_3]^{2+}$ and 507 nm for $[Fe(phen)_3]^{2+}$.[13] The formation of $TCNE^{-\cdot}$ in the reduction of TCNE by BNAH in MeCN was monitored at $\lambda_{max.}$ 457 nm [15] under pseudo-first-order conditions using a >10-fold excess of TCNE. The effects of pyridine derivatives on the rates of both reactions were examined by using an excess of

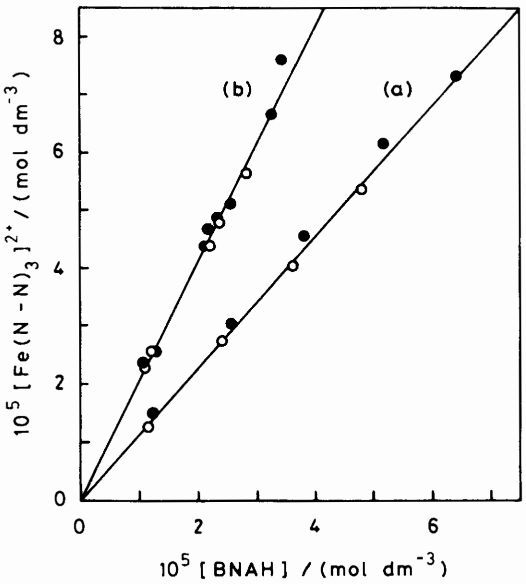

Figure 1. Plots of the concentration of $[Fe(N{-}N)_3]^{2+}$ formed in the electron-transfer reactions of BNAH with excess of $[Fe(bpy)_3]^{3+}$ (●) and $[Fe(phen)_3]^{3+}$ (○) *versus* [BNAH] (a) in the absence of base and (b) in the presence of pyridine (4.14×10^{-2} mol dm^{-3}) or 3-cyanopyridine (3.3×10^{-1} mol dm^{-3})

the pyridine derivative relative to BNAH. Pseudo-first-order rate constants were determined by least-squares curve fitting using a Union System 77 microcomputer.

Results and Discussion

Electron-transfer Reactions from BNAH to $[Fe(N{-}N)_3]^{3+}$.—Upon mixing BNAH with $[Fe(bpy)_3](PF_6)_3$ or $[Fe(phen)_3](ClO_4)_3$ in MeCN at 298 K, an intense absorption band due to the reduced iron(II) species was almost immediately observed at $\lambda_{max.} = 520$ nm (ε 9.05×10^4 mol^{-1} dm^2) for $[Fe(bpy)_3]^{2+}$ or 507 nm (ε 1.31×10^5 mol^{-1} dm^2) for $[Fe(phen)_3]^{2+}$. The stoicheiometry of the oxidation of BNAH by $[Fe(N{-}N)_3]^{3+}$ determined from the electronic absorption spectra (Figure 1a) suggests that one-electron transfer (et.) from BNAH to $[Fe(N{-}N)_3]^{3+}$ occurs, equation (1). The radical cation

$$BNAH + [Fe(N{-}N)_3]^{3+} \xrightarrow{k_{et.}} BNAH^{+\cdot} + [Fe(N{-}N)_3]^{2+} \quad (1)$$

$BNAH^{+\cdot}$ formed by the electron transfer is known to disproportionate to yield BNA^+ and $(BNAH)H^+$, equation (2),[10] where the formation of BNA^+ was confirmed by n.m.r.

$$2BNAH^{+\cdot} \longrightarrow BNA^+ + (BNAH)H^+ \quad (2)$$

measurements (see Experimental section). Thus, BNAH acts as a one-electron donor towards $[Fe(N{-}N)_3]^{3+}$, and $BNAN^{+\cdot}$ is not further oxidized by $[Fe(N{-}N)_3]^{3+}$.

In the presence of excess of pyridine, the number of equivlents of $[Fe(N{-}N)_3]^{3+}$ reduced per mole of BNAH changes from one in the absence of pyridine to two as shown in Figure 1b. Such a change of stoicheiometry has also been observed for the electrochemical oxidation of BNAH in the absence and the presence of pyridine.[10] Since the radical cation $BNAH^{+\cdot}$ is known to be deprotonated readily in the presence of pyridine,[6,10] the change of the stoicheiometry on addition of a base can be explained by reactions (3) and (4), where B

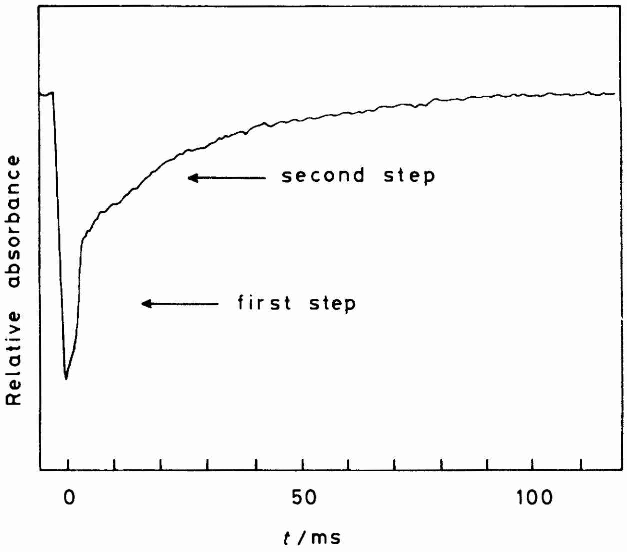

Figure 2. Kinetic curve for two-step oxidation of BNAH (2.00×10^{-4} mol dm^{-3}) by $[Fe(bpy)_3]^{3+}$ (7.45×10^{-4} mol dm^{-3}) in the presence of 3-cyanopyridine (6.30×10^{-3} mol dm^{-3}), followed by the increase in absorbance at 520 nm due to $[Fe(bpy)_3]^{2+}$

$$BNAH^{+\cdot} + B \xrightarrow{k_B} BNA^{\cdot} + BH^+ \quad (3)$$

$$BNA^{\cdot} + [Fe(N{-}N)_3]^{3+} \xrightarrow{fast} BNA^+ + [Fe(N{-}N)_3]^{2+} \quad (4)$$

denotes a base. Such a multistep electron transfer is confirmed by the kinetics of the formation of $[Fe(N{-}N)_3]^{2+}$ in the presence of a base as shown in Figure 2, which shows a two-step oxidation by $[Fe(N{-}N)_3]^{3+}$. The first step corresponds to the initial one-electron transfer from BNAH to $[Fe(N{-}N)_3]^{3+}$ [equation (1)]. The rate constants of the first step ($k_{et.}$) for the oxidation of BNAH by both $[Fe(bpy)_3]^{3+}$ and $[Fe(phen)_3]^{3+}$ were too fast to be determined accurately by using a stopped flow spectrophotometer; $k_{et.} > 1 \times 10^7$ mol^{-1} dm^3 s^{-1}. Indeed, such fast electron-transfer reactions are expected from the negative values of the free-energy change of the electron-transfer reactions; $\Delta G^0 = -44$ and -45 kJ mol^{-1} for $[Fe(bpy)_3]^{3+}$ and $[Fe(phen)_3]^{3+}$, respectively, obtained from the relation $\Delta G^0 = F(E_{ox.}{}^0 - E_{red.}{}^0)$ where $E_{ox.}{}^0$ and $E_{red.}{}^0$ are the oxidation potential of BNAH (+0.6 V *vs.* saturated calomel electrode, S.C.E.)[16] and the reduction potentials of $[Fe(bpy)_3]^{3+}$ (+1.06 V) or $[Fe(phen)_3]^{3+}$ (+1.07 V).[13]

The second step in Figure 2, which was observed only in the presence of a base, may be ascribed to the reactions (3) and (4), in which the deprotonation of $BNAH^{+\cdot}$ by a base is considered to be rate-determining. The rate of the electron-transfer from $BNA^{\cdot}$ to $[Fe(N{-}N)_3]^{3+}$ [equation (4)] may be diffusion-limited since the free-energy change of the electron transfer is largely negative; $\Delta G^0 = -218$ kJ mol^{-1} for $[Fe(bpy)_3]^{3+}$ and -219 kJ mol^{-1} for $[Fe(phen)_3]^{3+}$, which are obtained from the oxidation potential of $BNA^{\cdot}$ (−1.2 V *vs.* S.C.E.)[17] and the reduction potentials of $[Fe(N{-}N)_3]^{3+}$ as described above. Rates of the second step in the electron-transfer reactions from BNAH to $[Fe(bpy)_3]^{3+}$ obeyed pseudo-first-order kinetics in the presence of excess of base and the pseudo-first-order rate constants $k_{obs.}$ are proportional to the base concentration as shown in Figure 3. Thus, the proton transfer rate constant k_B can be determined from $k_{obs.}$ by the relation $k_{obs.} = k_B[B]$. The k_B values of pyridine for $[Fe(phen)_3]^{3+}$ and $[Fe(bpy)_3]^{3+}$ were the same, $(1.0 \pm 0.3) \times 10^6$ mol^{-1} dm^3 s^{-1}, independent of the oxidant. The results for

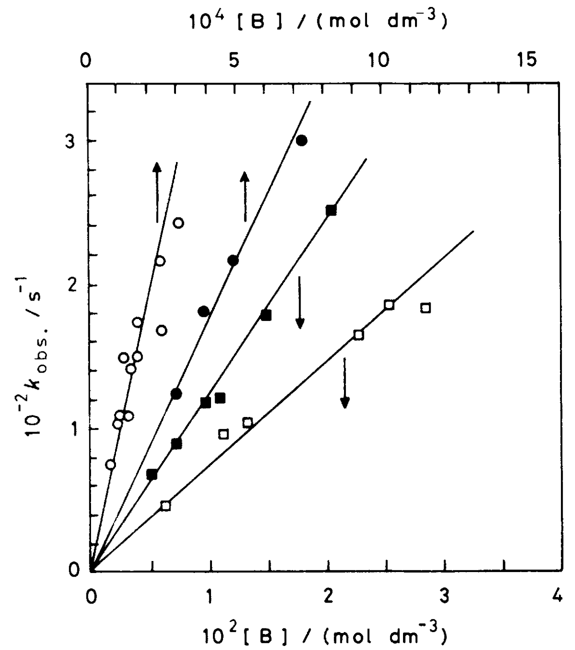

Figure 3. Plots of pseudo-first-order rate constants $k_{obs.}$ for the second step in the electron-transfer reaction of BNAH with $[Fe(bpy)_3]^{3+}$ *versus* the concentrations of base: (○) pyridine, (●) 4-acetylpyridine, (■) 4-cyanopyridine, (□) 3-cyanopyridine

Table. Proton transfer rate constants k_B for deprotonation of $BNAH^{+\bullet}$ by pyridine derivatives determined from the electron-transfer reactions from BNAH to $[Fe(bpy)_3]^{3+}$ and k_B' from the reduction of TCNE by BNAH in the presence of pyridine derivatives, and the primary kinetic isotope effects k_H/k_D

Entry	Base	pK_a [a]	log k_B [b]	log k_B' [c]	k_H/k_D [d]
1	3,5-Dichloropyridine	0.67	3.2	2.7	1.7
2	3-Cyanopyridine	1.45	3.8	3.6	1.8
3	4-Cyanopyridine	1.86	4.1	4.3	1.8
4	3-Bromopyridine	2.84	5.0	4.9	2.0
5	3-Acetylpyridine	3.18	5.4	5.5	2.0
6	4-Acetylpyridine	3.51	5.6	5.6	2.0
7	Pyridine	5.29	6.0	6.2	1.7
8	2-Aminopyridine	6.82	6.1	6.2	1.6
9	4-Aminopyridine	9.17	6.2	6.8	1.3

[a] Ref. 18. [b] log(k_B/mol^{-1} dm^3 s^{-1}) determined with accuracy ±0.1. [c] Determined from the $k_B'K$ and K values obtained from the plots in Figures 6 and 8, respectively; see text; the experimental errors in log(k_B'/mol^{-1} dm^3 s^{-1}) are ±0.1. [d] Determined from the ratio of the rate constant $k_B'K$ for BNAH to that for [4,4-$^2H_2$]BNAH with accuracy ±0.1.

various bases and $[Fe(bpy)_3]^{3+}$ are listed in the Table together with the pK_a values of the bases.[18]

Hydride Transfer from BNAH to TCNE.—Upon mixing of BNAH with TCNE in MeCN, TCNE was reduced to $TCNE^{-\bullet}$, showing the characteristic spectrum containing twelve absorption maxima between 350 and 500 nm (*e.g.* $\lambda_{max.}$ 457 nm, ε 5.67 × 10^4 mol^{-1} dm^2).[15] The stoicheiometry of the reduction by BNAH determined from the electronic spectra (Figure 4) is given by equation (5).

$$BNAH + 3/2TCNE \longrightarrow BNA^+ + TCNE^{-\bullet} + 1/2TCNEH_2 \quad (5)$$

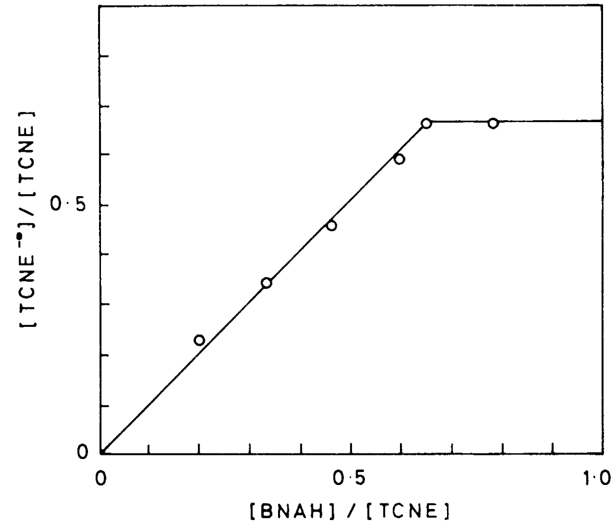

Figure 4. Plot of the ratio of the concentration of $TCNE^{-\bullet}$ formed in the reduction of TCNE by BNAH in MeCN to the initial concentration of TCNE (7.58 × 10^{-5} mol dm^{-3}) *versus* the ratio of the BNAH concentration to the initial concentration of TCNE

In contrast to the electron-transfer reactions from BNAH to $[Fe(N-N)_3]^{3+}$ [equation (1)], the stoicheiometry of the reduction of TCNE by BNAH in the absence of a base [equation (5)] suggests that BNAH acts as a two-electron donor, since BNAH reduces TCNE into one $TCNE^{-\bullet}$ (one-electron reduction product) and one-half a $TCNEH_2$ molecule (two-electron reduction product). Thus, the reduction of TCNE by BNAH is suggested to occur *via* a transfer of a hydride ion (two-electron equivalent) from BNAH to TCNE [reaction (6)], followed by fast electron transfer from $TCNEH^-$ to TCNE [reaction (7)], and the subsequent disproportionation of $TCNEH^\bullet$ [reaction (8)].

$$BNAH + TCNE \xrightarrow{k} BNA^+ + TCNEH^- \quad (6)$$

$$TCNEH^- + TCNE \xrightarrow{fast} TCNEH^\bullet + TCNE^{-\bullet} \quad (7)$$

$$2TCNEH^\bullet \xrightarrow{fast} TCNEH_2 + TCNE \quad (8)$$

It should be noted that the same stoicheiometry as in equation (5) has been observed for hydride-transfer reactions from BNAH to various *p*-benzoquinone derivatives.[19] The rate constant, k, for the hydride transfer has been determined from the rate of the formation of $TCNE^{-\bullet}$ as 2.1 × 10^2 mol^{-1} dm^3 s^{-1} at 298 K. The primary kinetic isotope effect k_H/k_D has also been determined from the ratio of the rate constant of BNAH to that of [4,4-$^2H_2$]BNAH as 2.0 ± 0.2, assuming that the secondary isotope effect is unity.

In the presence of a base, the stoicheiometry of the reduction of TCNE by BNAH changes from equation (5) in the absence of a base to equation (9), as shown in Figure 5.

$$BNAH + 2TCNE + B \longrightarrow BNA^+ + 2TCNE^{-\bullet} + BH^+ \quad (9)$$

A more remarkable effect of the addition of a base to the BNAH–TCNE system is observed on the rate constants for the formation of $TCNE^{-\bullet}$ as shown in Figure 6, where the rate constants k increase linearly with the base concentration. Such an enhancement of the rate of the formation of $TCNE^{-\bullet}$ by the addition of a base can hardly been reconciled by the

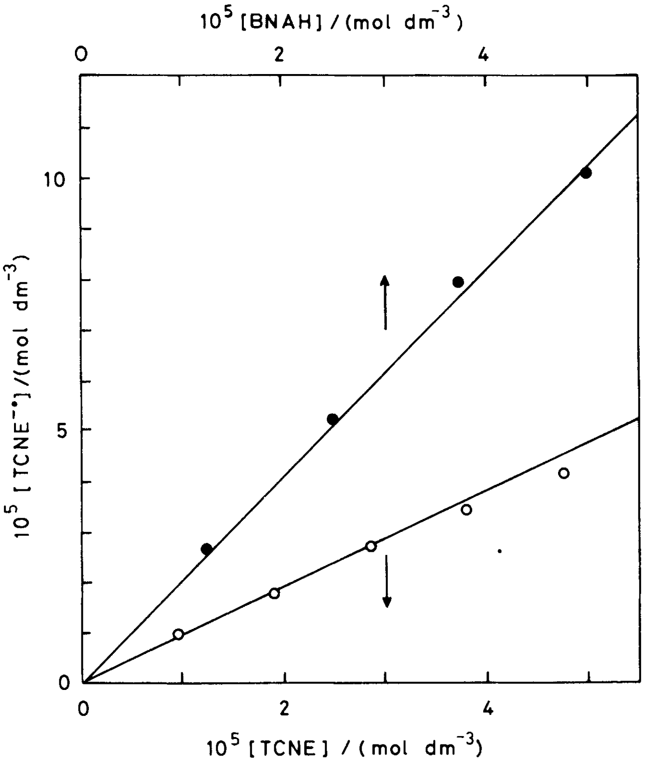

Figure 5. Plots of the concentration of TCNE$^{-\cdot}$ formed in the reduction of TCNE by BNAH in the presence of pyridine (4.1×10^{-2} mol dm^{-3}) *versus* [BNAH] (●) and [TCNE] (○)

hydride transfer from BNAH to TCNE [equation (6)] being a one-step process, since neither BNAH nor TCNE interacts with a base. A possible intermediate in the reduction of TCNE by BNAH may be BNAH$^{+\cdot}$, which can interact with base prior to deprotonation of BNAH$^{+\cdot}$ by base as described above. Thus, the hydride transfer from BNAH to TCNE is suggested to occur *via* the electron–proton–electron sequence shown in equations (10)—(12). The apparent contradiction that BNAH

$$\mathrm{BNAH} + \mathrm{TCNE} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} [\mathrm{BNAH}^{+\cdot}\mathrm{TCNE}^{-\cdot}] \xrightarrow{k_2} [\mathrm{BNA}^{\cdot}\,\mathrm{TCNEH}^{\cdot}] \xrightarrow{\text{fast}} \mathrm{BNA}^+ + \mathrm{TCNEH}^- \quad (10)$$

In the presence of a base:

$$[\mathrm{BNAH}^{+\cdot}\,\mathrm{TCNE}^{-\cdot}] + \mathrm{B} \xrightarrow{k_{\mathrm{B}}'} \mathrm{BNA}^{\cdot} + \mathrm{TCNE}^{-\cdot} + \mathrm{BH}^+ \quad (11)$$

$$\mathrm{BNA}^{\cdot} + \mathrm{TCNE} \xrightarrow{\text{fast}} \mathrm{BNA}^+ + \mathrm{TCNE}^{-\cdot} \quad (12)$$

appears to be a one-electron donor and a two-electron donor in the reactions with $[\mathrm{Fe(N{-}N)_3}]^{3+}$ [equation (1)] and TCNE [equation (5)], respectively, may well be reconciled by equations (10)—(12), since TCNE$^{-\cdot}$ in the radical ion pair [BNAH$^{+\cdot}$ TCNE$^{-\cdot}$] acts as a base in the BNAH–TCNE system without any other bases. In the presence of a base such as pyridine, the deprotonation of BNAH$^{+\cdot}$ by base [equation (11)] may compete with or exceed the intramolecular deprotonation of BNAH$^{+\cdot}$ by TCNE$^{-\cdot}$ in the radical ion pair [equation (10)], followed by the fast electron transfer from BNA$^{\cdot}$ to TCNE [equation (12)] as in the case of the electron-transfer reactions of BNAH with $[\mathrm{Fe(N{-}N)_3}]^{3+}$ in the presence of a base [equation (4)]. On the other hand, one molecule of TCNEH$^-$ formed in the hydride-transfer reaction (10) may be converted into two molecules of TCNE$^{-\cdot}$ by the reaction with TCNE and base [equation (13)] as required in the stoicheiometry of the reaction (9).

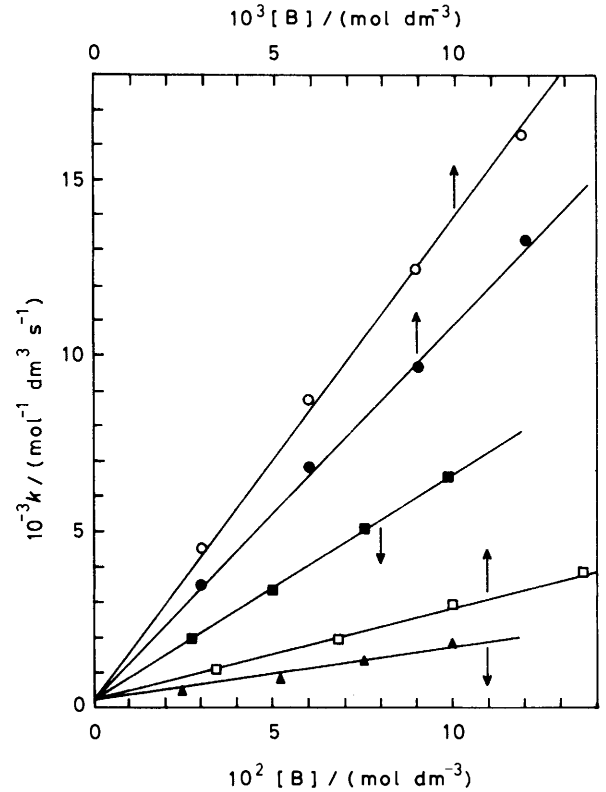

Figure 6. Variation of the rate constant *k* for the reduction of TCNE by BNAH in MeCN containing pyridine derivatives at 298 K, as a function of the base concentration: (○) 4-acetylpyridine, (●) 3-acetylpyridine, (■) 4-cyanopyridine, (□) 3-bromopyridine, (▲) 3-cyanopyridine

$$\mathrm{TCNEH}^- + \mathrm{TCNE} + \mathrm{B} \xrightarrow{\text{fast}} 2\mathrm{TCNE}^{-\cdot} + \mathrm{BH}^+ \quad (13)$$

According to equations (10)—(12), the rate of formation of TCNE$^{-\cdot}$ in the presence of a base B is given by equation (14). By applying a steady-state approximation to [BNAH$^{+\cdot}$

$$\mathrm{d[TCNE^{-\cdot}]/d}t = 2(k_2 + k_{\mathrm{B}}'[\mathrm{B}])[\mathrm{BNAH}^{+\cdot}\,\mathrm{TCNE}^{-\cdot}] \quad (14)$$

TCNE$^{-\cdot}$] in equations (10)—(12), the steady-state concentration of [BNAH$^{+\cdot}$ TCNE$^{-\cdot}$] is given by equation (15). In the presence of excess of TCNE, the final concentration

$$[\mathrm{BNAH}^{+\cdot}\,\mathrm{TCNE}^{-\cdot}] = \frac{k_1[\mathrm{BNAH}][\mathrm{TCNE}]}{k_{-1} + k_2 + k_{\mathrm{B}}'[\mathrm{B}]} \quad (15)$$

of TCNE$^{-\cdot}$ ($[\mathrm{TCNE}^{-\cdot}]_\infty = 2[\mathrm{BNAH}]_0$) is given by equation (16), based on the stoicheiometry of the reaction [equation (9)]. From equations (14)—(16) is derived equation (17). Thus, the

$$[\mathrm{TCNE}^{-\cdot}]_\infty = 2[\mathrm{BNAH}] + 2[\mathrm{BNAH}^{+\cdot}\,\mathrm{TCNE}^{-\cdot}] + [\mathrm{TCNE}^{-\cdot}] \quad (16)$$

$$\frac{\mathrm{d[TCNE^{-\cdot}]}}{\mathrm{d}t} = \frac{k_1(k_2 + k_{\mathrm{B}}'[\mathrm{B}])[\mathrm{TCNE}]}{k_{-1} + k_2 + k_{\mathrm{B}}'[\mathrm{B}] + k_1[\mathrm{TCNE}]}([\mathrm{TCNE}^{-\cdot}]_\infty - [\mathrm{TCNE}^{-\cdot}]) \quad (17)$$

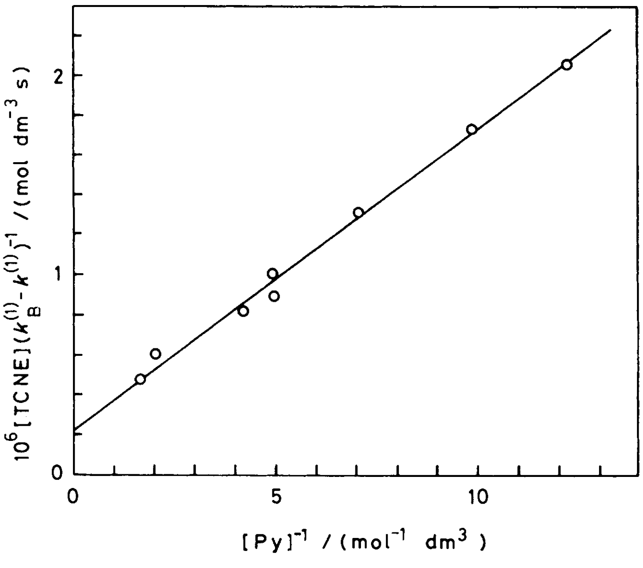

Figure 7. Plot of [TCNE]/($k_B^{(1)} - k^{(1)}$) *versus* 1/[Py] for the reduction of TCNE by BNAH in the presence of pyridine (Py) in MeCN at 298 K; see equation (21) in text

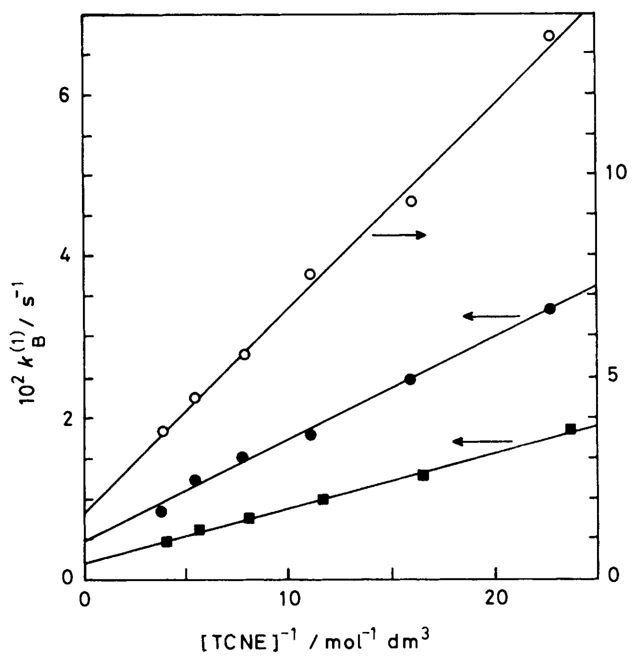

Figure 8. Plots of $1/k_B^{(1)}$ *versus* 1/[TCNE] for the reduction of TCNE by BNAH in the presence of pyridine derivatives: (○) 3.10 × 10^{-3} mol dm^{-3} of 3-cyanopyridine, (●) 7.54 × 10^{-3} mol dm^{-3} of 4-cyanopyridine, (■) 3.86 × 10^{-3} mol dm^{-3} of 3-bromopyridine

pseudo-first-order rate constant $k_B^{(1)}$ in the presence of excess of TCNE is given by equation (18).

$$k_B^{(1)} = \frac{k_1(k_2 + k_B'[B])[TCNE]}{k_{-1} + k_2 + k_B'[B] + k_1[TCNE]} \quad (18)$$

The linear correlation between k (= $k_B^{(1)}$/[TCNE]) and the base concentration in Figure 6 accords with equation (18) under the condition $k_{-1} \gg k_2 + k_B'[B] + k_1[TCNE]$, when equation (18) is reduced to equation (19), where K (= k_1/k_{-1})

$$k = K(k_2 + k_B'[B]) \quad (19)$$

is the formation constant of the radical ion pair [BNAH$^{+\cdot}$ TCNE$^{-\cdot}$]. With higher concentration of base, equation (18) under the condition $k_{-1} \gg k_2 + k_1[TCNE]$ may be rewritten as equation (20), where $k^{(1)}$ represents the pseudo-first-order rate constant in the absence of a base and the

$$k_B^{(1)} = k^{(1)} + \frac{k_1 k_B'[B]}{k_{-1} + k_B'[B]}[TCNE] \quad (20)$$

$k^{(1)}$/[TCNE] value accords with the rate constant k in the absence of a base [equation (6)], 2.1 × 10^2 mol^{-1} dm^3 s^{-1}.

$$\frac{[TCNE]}{k_B^{(1)} - k^{(1)}} = \frac{1}{k_B'K[B]} + \frac{1}{k_1} \quad (21)$$

Equation (20) may be rearranged as equation (21). The validity of equation (21) is shown by the linear plot between [TCNE]/($k_B^{(1)} - k^{(1)}$) and 1/[B] when pyridine was used as the base (Figure 7). The formation constant K for the radical ion pair [BNAH$^{+\cdot}$ TCNE$^{-\cdot}$] can be obtained from a linear plot between $1/k_B^{(1)}$ and 1/[TCNE] with a fixed base concentration, based on equation (22), which is derived from

$$\frac{1}{k_B^{(1)}} = \frac{1}{K(k_2 + k_B'[B])[TCNE]} + \frac{1}{(k_2 + k_B'[B])} \quad (22)$$

equation (18) under the condition $k_{-1} \gg k_2 + k_B'[B]$. Plots of equation (22) are shown in Figure 8, where three different pyridine derivatives are used as bases. The ratio of the intercept to the slope in each plot yields the K values (3.3 mol^{-1} dm^3 for 3-cyanopyridine, 3.4 for 4-cyanopyridine, and 3.1 for 3-bromopyridine), which are approximately the same, irrespective of the pyridine derivative, in accordance with equation (22).

Thus, the kinetics of the reduction of TCNE by BNAH in the presence of a base can be fully explained by equations (10)—(12). By using the K value evaluated from Figure 8, the proton transfer rate constants k_B' for various bases may be determined from the slopes in Figure 6, using equation (19). The results are listed in the Table, together with the rate constants k_B obtained independently from the electron-transfer reactions of BNAH with [Fe(N–N)$_3$]$^{3+}$ in the presence of various bases.

pK_a *of the Radical Cation of BNAH.*—The rate constants k_B and k_B' for proton transfer from BNAH$^{+\cdot}$ to various bases, determined by two independent methods {k_B from the electron-transfer reactions of BNAH with [Fe(N–N)$_3$]$^{3+}$ and k_B' from the reduction of TCNE by BNAH} are compared as a Brönsted plot between log(k_B or k_B') and pK_a of the bases, as shown in Figure 9. The agreement between the k_B and k_B' values of these two reactions provides strong evidence for the validity of the mechanism in equations (10)—(12). Proton transfers between normal acids and bases are known to give biphasic Brönsted plots with breaks at ΔpK_a = 0.[20] Such a break is observed also in Figure 9 at pK_a = 3.8 ± 0.3, which should correspond to the pK_a value of BNAH$^{+\cdot}$. This estimation is confirmed to be valid from the primary kinetic isotope effects on the proton-transfer reactions as follows. The k_H/k_D values have been determined from the ratio of the rate constant k_B of BNAH to that of [4,4-$^2H_2$]BNAH, which are also listed in the Table. Primary kinetic isotope effects on proton-transfer reactions are known to show a maximum value when the pK_a values of the proton donor and the pro-

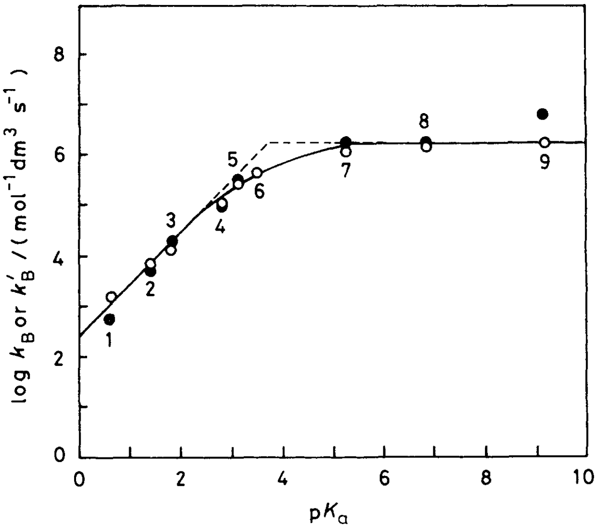

Figure 9. Brönsted plot of log k_B (○) or log k_B' (●) *versus* pK_a of bases. Numbers refer to pyridine derivatives in the Table

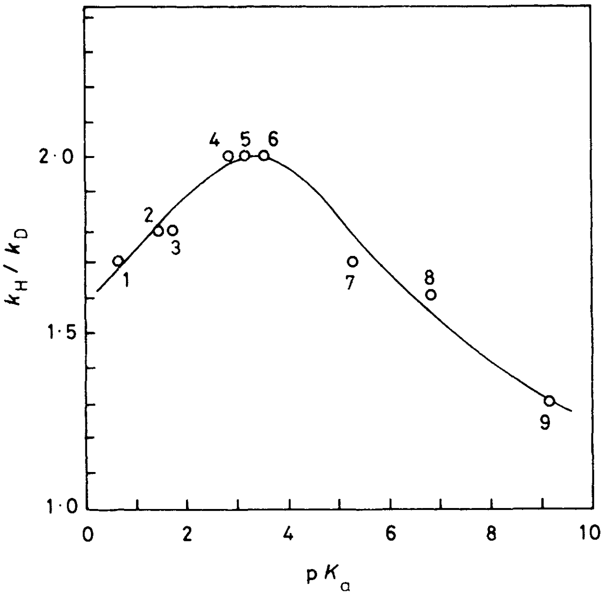

Figure 10. Variation of the primary kinetic isotope effect k_H/k_D for the proton transfer rate constant k_B', as a function of pK_a of base. Numbers refer to pyridine derivatives in the Table

tonated proton acceptor are approximately the same, *i.e.* ΔpK_a = 0. The plot of k_H/k_D against the pK_a of the bases in the present case also shows a maximum at pK_a = 3.5 ± 0.3 as illustrated in Figure 10. Thus, the pK_a of BNAH$^{+\cdot}$ can be evaluated as 3.6 ± 0.4. The maximum isotope effect (k_H/k_D = 2.0) observed in Figure 10 falls short of the value expected for a rate-determining proton transfer,[20] suggesting that the proton-transfer process is not fully rate-determining as observed for fast proton transfer between normal acids and bases.[21]

The pK_a value of BNAH$^{+\cdot}$ (3.6 ± 0.4) obtained in this study is consistent with the result that a plot of the primary kinetic isotope effects k_H/k_D in the reduction of a series of *p*-benzoquinone derivatives by BNAH in MeCN against the reduction potentials of the quinones shows a maximum for *p*-benzoquinone,[19] since the pK_a value of the semiquinone radical is known to be 3.9 ± 0.2.[22] The agreement of these two pK_a values suggests that the proton-transfer process from BNAH$^{+\cdot}$ to the radical anion of the substrate may be the rate-determining step for the hydride-transfer reactions from BNAH to *p*-benzoquinone derivatives as well as TCNE.

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