

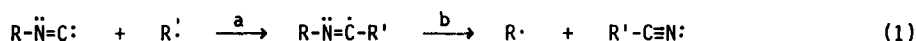
SECONDARY α -DEUTERIUM KINETIC ISOTOPE EFFECTS FOR ADDITION OF PHENYL
 RADICAL TO BENZYL ISOCYANIDES: AN EVIDENCE OF CONCERTED MECHANISM.¹

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Summary: Addition of phenyl radical to benzyl isocyanides gives benzonitrile and benzyl radicals, exhibiting positive Hammett $\rho = 0.26$ and notable secondary α -deuterium kinetic isotope effects. These can be rationalized by concerted bond formation/cleavage occurring with polar transition states(TS).

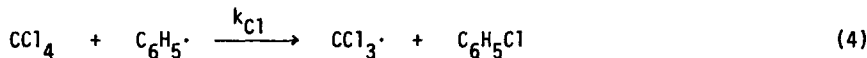
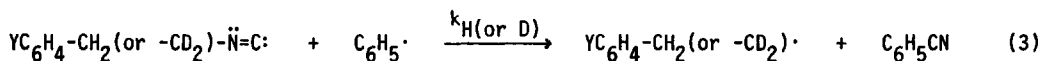
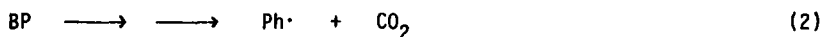
Homolytic additions to alkyl isocyanides² have been well investigated and the epr studies³ confirm imidoyl radicals as the bona fide intermediates. The intervention should thus unequivocally pronounce stepwise bond making, a, and breaking, b, for the reactions^{2,3} as in eq 1.



We now wish to report on our findings of the homolytic reactions of benzyl isocyanides in terms of Hammett correlations and secondary α -deuterium kinetic isotope effect abbreviated hereafter as α -D effect.

Numerous benzyl isocyanides with substituents being Y = p-OCH₃, p-CH₃, H, p-Cl, and p-CN, and their deuterated ones(YC₆H₄CD₂NC where Y = p-OCH₃, H, and p-CN) were prepared by the known procedures.⁴ Reactions at 100°C of degassed and sealed Pyrex tubes containing benzyl isocyanides(0.5 - 1.0 M), CCl₄(1.5 - 2.0 M), bromobenzene(3 mM) as an internal standard, and benzoyl peroxide(BP, 5 mM) in benzene, led to formations of benzonitrile and chlorobenzene via eqs 2-4.^{2(d,e)}

Scheme I.



(Y = p-OCH₃, p-CH₃, H, p-Cl, and p-CN)

Control experiment showed hydrogen abstraction at benzylic position by phenyl radical is of only minor importance and can not invalidate present competitive scheme. The α -additions⁵ at the terminal carbon can be also excluded.² The large ratios of [YPhCH₂NC + CCl₄] / [BP] \geq 400 can guarantee pseudo-first order kinetics⁶ so that eq 5 may be derived from 2-4.

$$k_{H(\text{or } D)} / k_{Cl} = \frac{[C_6H_5CN]}{[C_6H_5Cl]} \times \frac{[CCl_4]}{[YC_6H_4CH_2NC]} \quad (5)$$

The relative rate constants for hydrogen(or deuterium) vs. chlorine abstractions, i.e. $k_{\text{H}}(\text{or D})/k_{\text{Cl}}$, can be obtained via eq 5 from measurements⁷ of formations of $\text{C}_6\text{H}_5\text{CN}$ and $\text{C}_6\text{H}_5\text{Cl}$ with known initial concentrations of the two substrates. The rates and Hammett correlation are shown in Table I and Figure 1. Table I also contains $k_{\text{H}}/k_{\text{D}}$ derived from α -D effect, which is variable with substituents, Y= p-OCH₃, H, and p-CN.

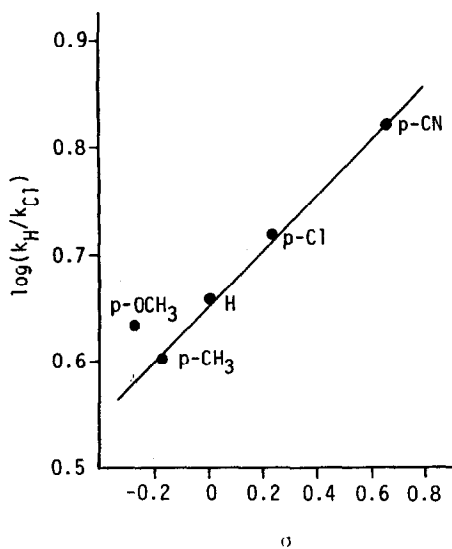


Figure 1. Hammett correlation for addition of phenyl radical to benzyl isocyanides in benzene at 100°C.

Table I. Relative Rates, Secondary α -Deuterium Kinetic Isotope Effects, and Hammett Correlations for Addition of Phenyl Radical to Benzyl Isocyanides in Benzene at 100°C.

Y:	p-OCH ₃	p-CH ₃	H	p-Cl	p-CN
$k_{\text{H}}/k_{\text{Cl}}$ ^a	4.28	4.02	4.56	5.24	6.64
$k_{\text{D}}/k_{\text{Cl}}$ ^a	3.32	-	4.24	-	5.31 ^c
$k_{\text{H}}/k_{\text{D}}$ ^{a,b}	1.289	-	1.075	-	1.251 ^c
Hammett Correlations ^d					
$\rho = 0.260$ ^{e,f}	$\rho^- = 0.196$ ^g	$\rho^+ = 0.143$ ⁱ			
$r = 0.996$ ^h	$r = 0.981$ ^h	$r = 0.878$ ^h			

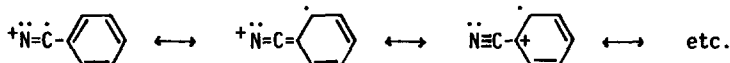
- Error limits are less than 2%, being average deviations of more than four runs.
- $k_{\text{H}}/k_{\text{D}} = k_{\text{H}}/k_{\text{Cl}} \cdot k_{\text{Cl}}/k_{\text{D}}$.
- k_{D} can be obtained from k_{obs} for 93% deuterated p-cyanobenzyl isocyanide using $k_{\text{H}}X_{\text{H}} + k_{\text{D}}X_{\text{D}} = k_{\text{obs}}$, with X indicating mole fraction.
- σ , σ^+ , and σ^- were taken from: Ritchie, C. D.; Sager, W. F. *Prog. Phys. Org. Chem.* 1964, 2, 334.
- The Hammett correlations do not include the rates for p-methoxybenzyl isocyanide. The reason has been stated during the discussion.
- $\log k_{\text{H}}/k_{\text{Cl}}$ was plotted against σ for p-CH₃, H, p-Cl, p-CN.
- $\log k_{\text{H}}/k_{\text{Cl}}$ was plotted against σ for p-CH₃, H, and p-Cl and σ^- for p-CN.
- Correlation coefficients. i. $\log k_{\text{H}}/k_{\text{Cl}}$ was plotted against σ^+ of all substituents.

The Hammett relations without p-methoxy substrate show excellent linearity with positive $\rho = 0.260$, which is best correlated with σ ($r = 0.996$) than either σ^+ ($r = 0.878$) or σ^- ($r = 0.981$). The conspicuous α -D effects may tell that C_{α} -N bond rupture must occur in rate determining step for eq 3. These observations, taken together, can be only rationalized in terms of a concerted manner, where attacking of phenyl radical occurs simultaneously with expulsion of benzyl radicals via intervention of 1 for other benzyl isocyanides than p-methoxy one. Since p-OCH₃ can more effectively destabilize benzylic anion moiety of 1 than p-CH₃, $k_{\text{H}}/k_{\text{Cl}}$ for p-OCH₃ might have been smaller than $k_{\text{H}}/k_{\text{Cl}} = 4.02$ for p-CH₃. The larger value of $k_{\text{H}}/k_{\text{Cl}} = 4.28 > 4.02$ can be however consistent with 2, which will be further substantiated later in terms of α -D effects.



The simultaneity in both cases of 1 and 2, appears parallel with two bond homolysis of tert-butyl

phenylperacetates involving benzyl radicals as leaving group.⁸ 1 can disperse positive charge into the phenyl ring as below, which may offer lower activation free energy than vice versa.



The positive $\rho = 0.5$ at 80°C has been once reported with the hydrogen abstractions from toluenes by tert-butyl radical,⁹ where the TS assumes similar polarization to 1. Electrophilic radicals¹⁰⁻¹⁴ such as Cl^\cdot , Br^\cdot , tert-BuO $^\cdot$, and $\text{C}_6\text{H}_5\text{COO}^\cdot$ show, on the other hand, negative ρ^+ values corresponding to the polarity of 2.

The α -D effects¹⁵ in Table I show $k_{\text{H}}/k_{\text{D}} > 1$ regardless of the substituents. This, so-called, normal α -D effect can arise because zero-point energy difference between $\text{C}_\alpha\text{-H}$ and $\text{C}_\alpha\text{-D}$ out-of-plane bending vibrations, is smaller in the TS than in the reactant. $\text{S}_{\text{N}}2$ reactions¹⁶⁻¹⁹ can exhibit $k_{\text{H}}/k_{\text{D}} > 1$ when the separation between the two proximal atoms of nucleophile and leaving group is relatively long, thus forming a comparatively loose TS. The magnitude of $k_{\text{H}}/k_{\text{D}}$ also tends to increase with longer distance between the two atoms. Homolysis of azo-bis- α -phenylethane exhibits $k_{\text{H}}/k_{\text{D}} = 1.27$ at 105°C ²⁰ and subsequent studies of α -phenylethyl azo-2-propane system by the same author^{21,22} suggest that the value of $k_{\text{H}}/k_{\text{D}}$ can be taken as a measure of extent of C-N bond breaking, viz. larger $k_{\text{H}}/k_{\text{D}}$ meaning equivalently more bond cleavage at alpha position (a keynote for our discussion).

Admitting similar environment around alpha hydrogens between TS of azo-bis- α -phenylethane²⁰ and benzyl isocyanide, comparison of $k_{\text{H}}/k_{\text{D}} = 1.075$ with $k_{\text{H}}/k_{\text{D}} = 1.27$ ²⁰ may announce correspondingly less²³ $\text{C}_\alpha\text{-N}$ bond breaking taking place in 1 with $\text{Y} = \text{H}$, which may then give rise to moderate charge separation for the TS with correspondingly small $\rho = 0.26$. While such slight rate increase has been observed with p-CN, that is, from $k_{\text{H}}/k_{\text{Cl}} = 4.56$ with $\text{Y} = \text{H}$ to 6.64 with $\text{Y} = \text{p-CN}$, it appears to exert plain influence on α -D effect, i.e. $k_{\text{H}}/k_{\text{D}} = 1.251$, whose magnitude is quite comparable with those of $\text{S}_{\text{N}}2$ reactions.¹⁶⁻¹⁹ p-OCH₃ renders the reactivity ($k_{\text{H}}/k_{\text{Cl}} = 4.28$) to significantly deviate from the Hammett line (see Figure 1) and boosts, nonetheless, the α -D effect to give $k_{\text{H}}/k_{\text{D}} = 1.289$. The anomaly can be tentatively explained by reversing the polarity with 2. p-OCH₃ can efficiently delocalize the positive charge so that 2 may require lower activation free energy than 1, which can be readily read from the positive deviation. p-Methoxybenzyl isocyanide may then experience more bond cleavage via 2 than benzyl isocyanide, 1, which is evident from $k_{\text{H}}/k_{\text{D}} = 1.289 > 1.075$.

α -D effects may therefore turn out to be a convenient diagnostic like activation parameters¹¹ for degree of the bond breaking at alpha carbon atom during transition states. Further work is progressing toward the full paper.

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