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Intramolecular Electron Transfer and S_N2 Reactions in the Radical Anions of 1-Benzoyl-ω-haloalkane Studied by Pulse Radiolysis

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A one-electron reduction of 1-benzoyl-ω-haloalkane (Cl, Br, I) by solvated electrons and a subsequent intramolecular reaction of the radical anions, thus formed, have been investigated by using a pulse radiolysis technique. The reaction mechanism, electron transfer (ET) or S_N2, and the rate constants were found to change as a function of the nature of the halide and the methylene chain length of the substrate. Although the order of reactivity based on leaving halogen atoms was I, Br, and Cl, the ease of the S_N2 reaction was found to be in the order Cl>Br>I. In addition, the reaction rates were also affected by the polarity of the solvent used. On the basis of these results, it is discussed how the ET–S_N2 dichotomy takes place.

Radical anions ($D^{\cdot-}$) are often used as electron-transfer (ET) reagents. They are easily generated by electrochemical and radiation-chemical reactions, as well as by the reaction of aromatic hydrocarbon with an alkali metal. The most widely investigated reaction is a reductive cleavage of a C–X bond in aliphatic halides (RX) (Eq. 1).[1–8] Mechanistic and kinetic information

$$D^{\cdot-} + RX \rightarrow D + R\cdot + X^- \qquad (1)$$

is available for this reaction from electrochemical[1–3] and pulse radiolysis[4–6] studies. There is a large variation in the reaction rate, depending on the oxidation potential of the radical anion donor ($D^{\cdot-}$) and the reduction potential of the alkyl halide acceptor (RX).

On the other hand, Lund and Simonet[9] have studied an electrochemical reaction of fluorenone with alkyl halide and confirmed a C–O bond formation at an α-carbon atom of the halide. An S_N2 reaction of the fluorenone radical anion with alkyl halide was proposed in order to explain the results. This reaction mechanism was also supported by the results from pulse radiolysis.[5]

In a previous investigation concerning the intramolecular reaction in the radical anions of 1-(4-biphenylyl)-ω-haloalkane,[10] an S_N2 reaction yielding a spirocyclic radical occurred competitively to an ET reaction, leading to a terminal carbon radical. However, no such a competitive intramolecular reaction was investigated in other reaction systems.

In the present work, we investigated the one electron reduction of 1-benzoyl-ω-haloalkane (Ph–CO–$(CH_2)_n$–X (BZ_X-*n*), X=Cl, Br, I; *n*=2, 3, 4) by solvated electrons and the subsequent intramolecular reaction of the radical anions, thus formed, by using a pulse radiolysis technique. Further, in order to obtain information concerning the reaction mechanism, the solvent effects on the reaction rates were also investigated.

Results and Discussion

Effects of Chain Length, *n*, and Leaving Halogen Atom. Hexamethylphosphoric triamide (HMPA) solutions of BZ_X-*n* were irradiated with an 8-ns electron pulse at room temperature. The transient absorption spectra of BZ_X-*n* (X=Cl, Br, I; *n*=3, 4) recorded at various times after the pulse are presented in Fig. 1. The spectra observed immediately after the pulse exhibit λ_{max} at 330 and 490 nm, and agree very closely with the spectrum of the radical anion of acetophenone (λ_{max}=330 and 490 nm) which was measured in this work under the same

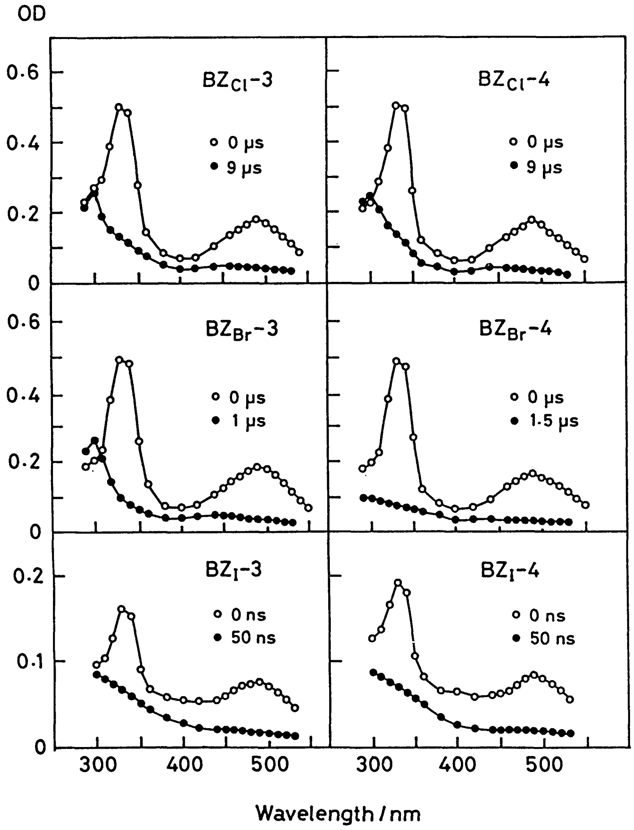


Fig. 1. Transient absorption spectra recorded at various times after the irradiation of an 8-ns electron pulse to HMPA solutions (3×10^{-3} mol dm^{-3}) containing 1-benzoyl-ω-haloalkane (BZ_X-*n*, X=Cl, Br, I; *n*=3, 4) at room temperature.

reaction conditions. The initial intensities of these bands observed from BZ_{Cl}-3, BZ_{Cl}-4, BZ_{Br}-3, and BZ_{Br}-4 are almost the same to those of the acetophenone radical anion. However, the initial intensities of the 330 and 490 nm bands observed from BZ_{I}-3 and BZ_{I}-4 are weaker than those of BZ_{Cl}-*n* and BZ_{Br}-*n*, which possess the same chain length (*n*), respectively. This can be explained by the short lifetime of the radical anion (**1** in Scheme 1), as described later. The decay of the 330 and 490 nm bands of all radical anions (**1**) followed first-order kinetics, and the rates were independent of both the solute concentration (1×10^{-2}—1×10^{-3} mol dm^{-3}) and absorption dose. These results indicate that the decay reaction of the radical anion (**1**) proceeds unimolecularly.

On the other hand, in the case of BZ_{Br}-3, the decay of the initial bands are characterized by the formation of a new band with λ_{max} at 300 nm. Further, a similar 300 nm band was also observed in the cases of BZ_{Cl}-3 and BZ_{Cl}-4. This new band coincides with that of an α-methoxybenzyl radical, $Ph\dot{C}H(OMe)$ (λ_{maxc}=300 nm), formed by a one-electron reduction of benzaldehyde dimethyl acetal. The similarity between both spectra indicates the formation of a similar species, i.e., a cyclic ether radical (**3** in Scheme 1; 2-phenyltetrahydro-2-furyl and 2-phenyltetrahydro-2-pyranyl radicals).

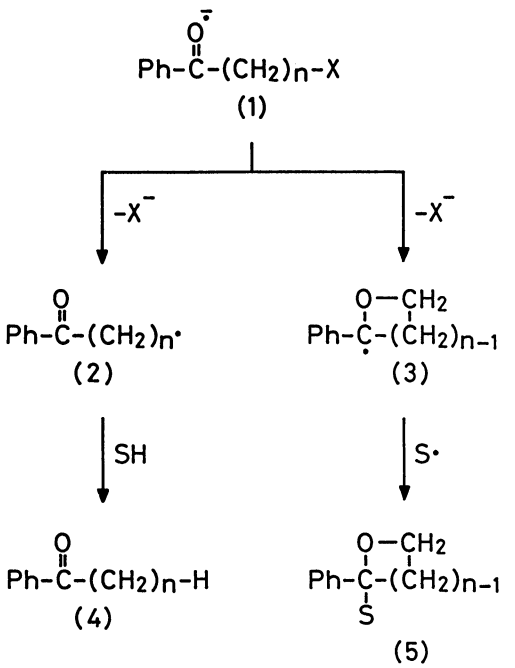
The rate constants (*k*, s^{-1}) measured from the decay of the 490 nm bands are summarized in Table 1, together with the yields of the alkyl phenyl ketone (**4**) by γ-irradiation. In the cases of BZ_{Cl}-2, BZ_{Br}-2, BZ_{Br}-4, BZ_{I}-3, and BZ_{I}-4, the *G*-values (1.8—2.1) of the formation of (**4**) are close to the *G*-value of the solvated electron, i.e., $G(e_s^-)=2.3$ in HMPA.[11] Therefore, in these compounds, it is clear that an intramolecular ET reaction leading to the production of a terminal carbon radical (**2**) preferentially occurs (Scheme 1).

On the other hand, in the cases of BZ_{Cl}-3, BZ_{Cl}-4, and BZ_{Br}-3, the yields of (**4**) were very low ($G<0.1$); the values are quite different from the *G*-values (2.3—2.5) of the substrate disappeared. In these compounds, a formation of the 300 nm bands assigned to a cyclic ether radical (**3**) was observed. Although the final products of this radical have not been confirmed, the mass spectra of the main products showed the formation of an adduct with a solvent radical (S·). These results provide clear evidence which support the idea that an intramolecular nucleophilic substitution (i.e., S_N2) is the main chemical process in these compounds.

Table 1. Pulse Radiolysis$^{a)}$ and γ-Radiolysis$^{b)}$ of BZ_X-*n* in HMPA Solution at Room Temperature

X	*n*	k/s^{-1}	G(ketone 4)$^{c)}$
Cl	2	8.3×10^6	2.0
Cl	3	2.9×10^5	<0.1 (2.3)$^{d)}$
Cl	4	2.5×10^5	<0.1 (2.5)$^{d)}$
Br	2	1.8×10^7	2.0
Br	3	3.2×10^6	<0.1 (2.4)$^{d)}$
Br	4	2.9×10^6	1.8
I	3	8.6×10^7	1.9
I	4	6.0×10^7	2.1

a) Absorption dose was 0.7 kGy/pulse. Substrate concentration: 3.0×10^{-3} mol dm^{-3}. b) Absorption dose was 2.3 kGy. Substrate concentration: 5.0×10^{-2} mol dm^{-3}. c) The 100 eV yield of alkyl phenyl ketone. d) The *G* value of the substrate disappeared.



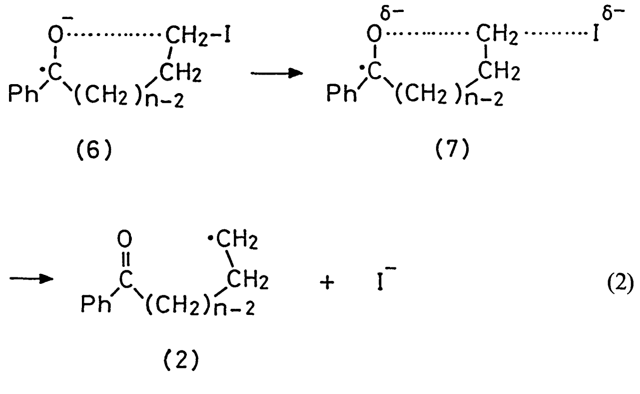
Scheme 1.

As described previously, the reaction mechanism and the decay rate constants of the radical anion (**1**) were found to change by the nature of the halide and the methylene chain length (*n*). The decay rate constants of the radical anion (**1**) with the same chain length are in the order I > Br > Cl, which is consistent with the ease of reducing the alkyl halides.[2] On the other hand, the intramolecular S_N2 reaction occurred predominantly in BZ_{Cl}-3, BZ_{Cl}-4, and BZ_{Br}-3. Thus, the S_N2 reaction seems to require a reaction system in which an efficient release of a halide ion does not occur. Further, in the present reaction system, an important factor for an S_N2 reaction is the contribution of a cyclic structure which assists a favorable conformation for a backside attack onto a terminal carbon atom, i.e. , at least a five- or six-membered ring is required.

On the other hand, Pross and Shaik[12,13] proposed that,at the transition state in nucleophilic substitution reactions, one half of the negative charge on the nucleophile anion is transfered to the substrate, and that a negative charge is localized in the leaving group, regardless of the position of the transition state along the reaction coordinate. However, when the nucleophile or leaving group is modified, so as to make the reaction faster, the product energy level becomes lower, and the transition state occurs earlier, in accord with the

Leffler–Hammond postulate.[14,15)]

According to the proposed theory, a negative charge is distributed to the carbonyl oxygen and the leaving halogen atom in equal amounts in the transition state. However, the reaction coordinate hardly progresses in the cases of BZ_I-3 and BZ_I-4, i.e., the transition state geometry (**7**) is close to that of a loose association complex (**6**) produced by an ion-dipole interaction (Eq. 2). Thus, it becomes harder to form a new bond, since the interaction of the two bonding orbitals ($O \cdots CH_2$) is weak and the O–C–I angle is different from 180° in the transition state. However, in the cases of BZ_{Cl}-3, BZ_{Cl}-4, and BZ_{Br}-3, the reaction coordinate progresses to satisfy the S_N2 conditions, which allow an attack of the central carbon in the axis of the C–X bond and a partial bond formation in the transition state.



(2)

On the other hand, molecular models indicate that the O–C–X angle in the six-membered-ring transition state slightly differs from 180°, while the O–C–X angle in the five-membered-ring transition state is very close to 180°. It, thus, appears that a six-membered ring is more difficult to form in the S_N2 transition state than a five-membered ring. For this reason, in the case of BZ_{Br}-4, which reacts more rapidly than does BZ_{Cl}-4, a new bond was not formed in the same manner as BZ_I-4. Further, the cyclic transition state of BZ_X-2 (X=Cl, Br) is too strained to form the S_N2 transition state, i.e., the carbonyl oxygen anion hits a terminal carbon from other direction than the axis.

The following conclusion thus emerges from these results. The ET and S_N2 reactions involve a common mechanism in which an electron is transfered from the carbonyl oxygen anion to a terminal carbon accompanied by a simultaneous fission of the C–X bond. Therefore, the S_N2 reaction is considered to be an extreme case in electron-transfer reactions accompanied by a fission of the C–X bond. That is, the S_N2 reaction selectively occurs when the conditions for the S_N2 reaction (described above) are satisfied.

Effeects of Solvent on the Reaction Rates. In order to make the reaction mechanism clear, solvent effects on the reaction rates were investigated using five different solvents such as DMA, DMF, DMSO, HMPA, and NMP (*N*-methyl-2-pyrrolidone). The transient absorption spectra observed immediately after the pulse were similar to that observed in HMPA. However, the decay rate constants of the 330 and 490 nm bands were dependent on the nature of the solvent used. A correlation of the rate constants ($\log k$) with an acceptor number (AN)[16)] of the solvent was examined in the same manner as in the case of a unimolecular dissociation of the radical anions of aryl chloride[17)] and chloroacetophenone isomers.[18)] In these cases, good linear correlations were obtained. Plots of $\log k$ measured from BZ_X-*n* (X=Cl, Br, I; *n*=3, 4) vs. AN are shown in Fig. 2. These plots show a quite different shape, depending on the nature of the leaving halogen atom. Similar correlations were also obtained when the Reichardt–Dimroth polarity parameter, $E_T(30)$,[19)] was used.

The extent of the solvation for anions is dependent on the charge density, which differs according to the ion radius and the structure.[20)] Such different solvations for anions in the transition state, intermediates, or reactants causes either a retardation or acceleration of the reaction rate.

In the case of BZ_{Cl}-*n* (*n*=2—4), it is apparent that the rate constants increase with increasing AN, namely the solvent polarity. Therefore, stronger solvations are

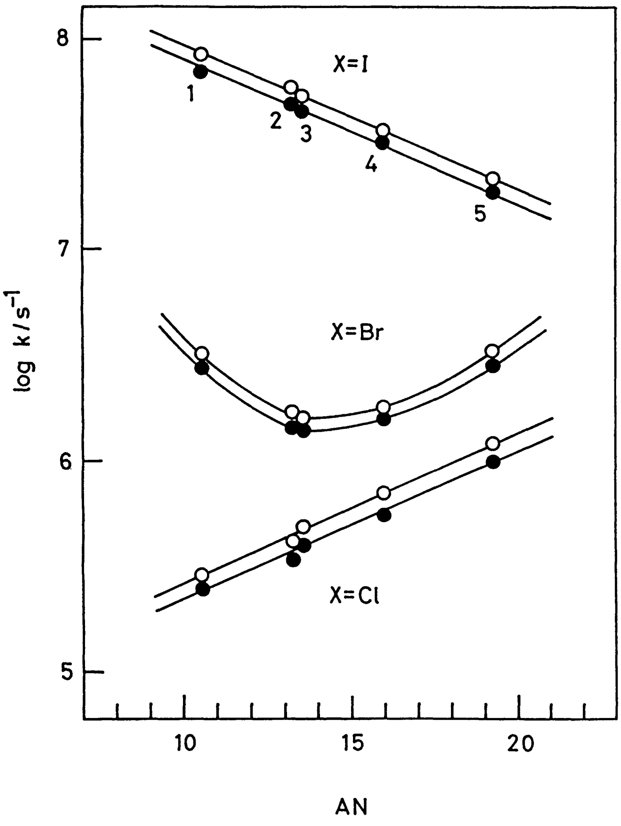


Fig. 2. Relationship between the decay rate constants ($\log k$) of the radical anions of BZ_X-3 (○; X=Cl, Br, I) and BZ_X-4 (●; X=Cl, Br, I) and acceptor number (AN) of the solvents: 1, HMPA; 2, NMP; 3, DMA; 4, DMF; 5, DMSO.

expected for the leaving chloride ion than for the ketone radical anion. Thus, an increase in the solvent polarity resulted in an increase in the rate. However, in the case of BZ_I-*n* (*n*=3, 4), the correlations are reversed. This means that the degree of solvation is higher for the ketone radical anion than for the iodide ion. Unlike these halides, U-shaped plots were obtained in the case of BZ_{Br}-*n* (*n*=2—4). Such a correlation is hardly explained at the moment, but may be the result of a difference in the solvation power for each individual anion of the solvent used.

However, plots of $\log k$ vs. the polarity parameters had the same shape for each halide, though the reaction mechanism is state in different terms (ET and S_N2) with different chain lengths (*n*). These results suggest that the bond-breaking process, concerted with an electron transfer which is involved in both the ET and S_N2 reactions, occurs as the rate-determining step.

These results strongly support the conclusion described in the preceding section. Accordingly, the fundamental mechanistic difference between the ET and S_N2 reactions is whether a new bond formation synchronized to the concerted electron transfer and bond-breaking processes occurs or not.

Experimental

Materials. 1-Benzoyl-2-chloroethane (BZ_{Cl}-2) from Tokyo Kasei was used without further purification. 1-Benzoyl-3-chloropropane (BZ_{Cl}-3) from Aldrich was purified by distillation under reduced pressure.

1-Benzoyl-4-chlorobutane (BZ_{Cl}-4). To a mixture of 8.0 g (0.06 mol) of $AlCl_3$ in dry benzene (100 ml) was added 7.0 g (0.05 mol) of 5-chlorovaleryl chloride at 0 °C. The mixture was stirred for 2 h at room temperature and then hydrized with ice water. The benzene layer was separated, washed with water, dried over sodium sulfate, and evaporated. The residue was recrystallized from pentane: Mp 49—50 °C (lit,[21] 50 °C) (Found: C, 67.20; H, 6.70; Cl, 18.01%).

1-Benzoyl-2-bromoethane (BZ_{Br}-2), 1-Benzoyl-3-bromopropane (BZ_{Br}-3), and 1-Benzoyl-4-bromobutane (BZ_{Br}-4). These compounds were prepared by using the previously described procedure for 3-bromopropionyl chloride, 4-bromobutyryl chloride, and 5-bromovaleryl chloride. BZ_{Br}-2: Mp 60—61 °C (lit,[22] 60 °C) (Found: C, 50.80; H, 4.30; Br, 37.56%). BZ_{Br}-3: Mp 38—39 °C (lit,[23] 38.5 °C) (Found: C, 52.62; H, 4.82; Br, 35.50%). BZ_{Br}-4: Mp 58—59 °C (lit,[21] 58.5 °C) (Found: C, 54.90; H, 5.55; Br, 32.90%).

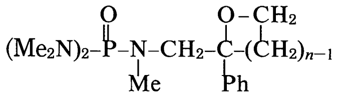
1-Benzoyl-3-iodopropane (BZ_I-3) and 1-Benzoyl-4-iodobutane (BZ_I-4). The corresponding bromides were refluxed in methyl ethyl ketone containing 10-fold excess of KI for 10 h. The organic layer was evaporated and the residue was recrystallized from pentane. BZ_I-3: Mp 51—52 °C (Found: C, 43.95; H, 4.20; I, 46.06%). BZ_I-4: Mp 71—72 °C (lit,[21] 71.5 °C) (Found: C, 46.14; H, 4.46; I, 44.29%).

Apparatus. The samples held in Suprasil quartz cells were irradiated with an 8-ns pulse of 28 MeV electrons from a linear accelerator of Osaka University. The transient species were monitored with a pulsed Xe lamp. The monitoring light was passed through a monochrometer (Nikon G-250) after being passed through the sample cell and monitored with an R928 photomultiplier (Hamamatsu Photonics). The output of the photomultiplier was digitized bya programable transient digitizer (Tektronix 7912AD) interfaced with a microcomputer (Sharp X68000ACE), which was also used to store the data on a disc and to analyze the data.

N,N-Dimethylacetamide (DMA), *N,N*-dimethylformamide (DMF), dimethyl sulfoxide (DMSO), hexamethylphosphoric triamide (HMPA) , and *N*-methyl-2-pyrrolidone (NMP) used as a solvent were distilled over CaH_2 under reduced pressure. Solutions were prepared immediately before irradiation and were degassed under high vacuum.

Product analysis was carried out by GLC (Shimazu GC-7A; using 1-m×3-mm glass column packed with 5% Silicone OV-1 on Chromosorb WAW DMCS, 60—80 mesh) and GLC-MS (JEOL JMS-DX300) after extraction by pentane from γ-irradiated HMPA solution.

The mass spectra of the main products (Yields: 60—70% based on the substrate disappeared) from BZ_{Cl}-3, BZ_{Cl}-4, and BZ_{Br}-3 showed the formation of an adduct (**5**) of a cyclic



$$(Me_2N)_2{-}\overset{\overset{\displaystyle O}{\|}}{P}{-}\underset{\underset{\displaystyle Me}{|}}{N}{-}CH_2{-}\overset{O-CH_2}{\underset{\underset{\displaystyle Ph}{|}}{C}}{-}(CH_2)_{n-1} \qquad (n{=}3 \text{ or } 4)$$

(**5**)

ether radical (**3**; see text) with HMPA. Results were as follows: adduct **5** (*n*=3); *m*/*z* 325 ($M^{+\cdot}$), 281 ($M^{+\cdot}-Me_2N$), 178 ($M^{+\cdot}-147$), 147 {$[Ph{-}C{-}(CH_2)_3{-}O]^+$}, 135 {$[(Me_2N)_2PO]^+$, major peak}, 105 [$(PhCO)^+$], 77 ($Ph^+$), 58 [$(Me_2NCH_2)^+$], 44 ($Me_2N^+$); adduct **5** (*n*=4); *m*/*z* 339 ($M^{+\cdot}$), 295 ($M^{+\cdot}-Me_2N$), 178 ($M^{+\cdot}-161$), 161 {$[Ph{-}C{-}(CH_2)_4{-}O]^+$}, 135 {$[(Me_2N)_2PO]^+$, major peak}, 105 [$(PhCO)^+$], 77 ($Ph^+$), 58 [$(Me_2NCH_2)^+$], 44 ($Me_2N^+$).

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