

Fragmentation of Anion Radicals with Elimination of Aryloxy Groups

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Abstract—4-Vinylbenzyl phenyl ether, 4-phenylbenzyl phenyl ether, 1- and 2-naphthylmethyl phenyl ethers react with sodium thiophenolate under photochemical stimulation with replacement of the phenoxy group. The composition of reaction products and relation of reactivity to the structure of substrates is consistent with anion-radical mechanism. The corresponding methoxy and cyano derivatives do not undergo the reaction.

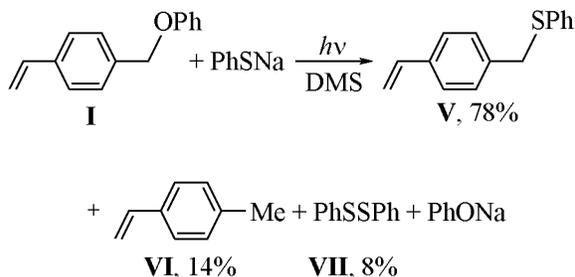
Unactivated aryl halides are known to easily enter into substitution reactions with some nucleophile reagents at photoinitiation or under action of solvated electrons, and the reaction proceeds along anion-radical chain mechanism ($S_{RN}1$) [1]. This substitution mechanism is rigorously confirmed only in some cases. In general as a rule the direct proofs of the presence of free radicals and anion radicals as kinetically independent intermediates in $S_{RN}1$ reactions are lacking. As with the other chain processes it is due to high reactivity and consequently to short life time and low stationary concentration of these species. Even if the anion-radical is detected in the reaction mixture, it should be proved that the species actually participates in the main and not a side process. In this connection arises a necessity of developing alternative procedure for proving the participation of anion radicals in the nucleophilic substitution.

In the study of reaction between bromobenzene and cyanomethyl anion was established that the reaction proceeded along anion-radical mechanism furnishing 1,2-diphenylethane as the main product [2]. From these data was made a conclusion that the intermediate anion-radical of phenylacetonitrile was able to undergo fragmentation with elimination of a cyanide anion. The possibility of such fragmentation we took as a base of a new confirmation procedure of anion radicals formation as intermediates in organic reactions [3]. The procedure consists in the reactivity study of $HgC_6H_6CH_2X$ type compounds where X is a leaving group of low nucleofugal properties unable to replacement by common mechanisms of nucleophilic substitution. The formation of products substituted at benzyl position may evidence that the reac-

tion proceeded via anion-radical intermediate. This approach was used in confirming the anion-radical mechanism of aromatic halides carbonylation in the presence of cobalt carbonyl [3], and in detection of anion-radical stages in reactions of nucleophilic vinyl substitution [4]. We also showed that analogous fragmentation is characteristic also of the other weakly nucleofugal leaving groups: OAlk, OAr, SAr [5]. Our data indicated that the tendency to fragmentation of the leaving group increased in the above series.

In the present study we investigated the fragmentation capability of anion radicals with weakly nucleofugal leaving groups located in the benzyl position on a wider range of substrates. To this end we studied reactions of sodium thiophenolate at photochemical stimulation with compounds containing phenoxy, methoxy, and cyano groups in the benzyl position: 4-vinylbenzyl phenyl ether (I), 4-phenylbenzyl phenyl ether (II), 1- and 2-naphthylmethyl phenyl ethers (III, IV), and also the corresponding cyano derivatives. It was established that under these conditions the reactions between aryl bromides and thiophenolate ion followed the $S_{RN}1$ mechanism [6]. It was reason-

Scheme 1.



able to assume that the other molecules with similar or more negative redox potentials would generate anion radicals under the conditions in question.

The reactivity of investigated substrates is governed by the nature of the leaving group. With cyano group attached to benzyl position the reaction failed to occur. No reaction was also observed with (1- and 2-methoxymethyl)naphthalenes. At the same time compounds **I–IV** react with sodium thiophenolate with replacement of the phenoxy group. The reaction products obtained from compound **I** are shown on Scheme 1.

Formation of compounds **V–VII** is consistent with the anion-radical reaction mechanism (Scheme 2).

The electron-transfer to molecule **I** furnishes the corresponding anion radical **A** that undergoes fragmentation to yield 4-vinylbenzyl radical **B**. Its reaction with thiophenolate ion followed by electron transfer to the substrate molecule affords reaction product **V**. 4-Vinyltoluene (**VI**) arises either due to the hydrogen transfer from solvent or by reduction of radical **B** with thiophenolate ion followed by proton transfer.

Analogously reacts compound **II** (Scheme 3) as is additionally proved by the presence among reaction products of compound **IX** arising from recombination of 4-phenylbenzyl radicals, and of a small amount (~1%) of 4-methylbiphenyl (**X**), product of reduction of these radicals.

The reaction between thiophenolate ion and compound **III** follows the same mechanism (Scheme 4, Table 1).

Scheme 2.

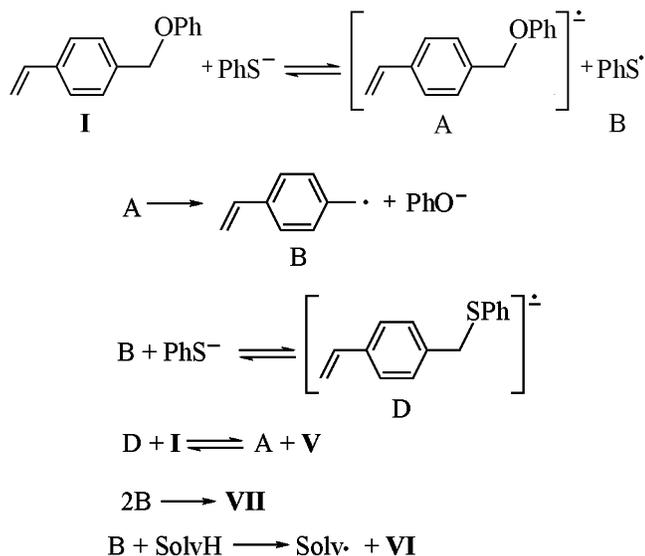
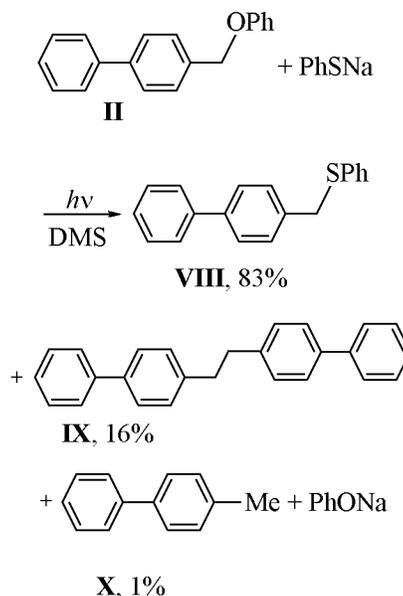


Table 1. The composition of reaction mixture (mol%) in reaction of 2-naphthylmethyl phenyl ether with sodium thiophenolate in DMSO at photoinitiation

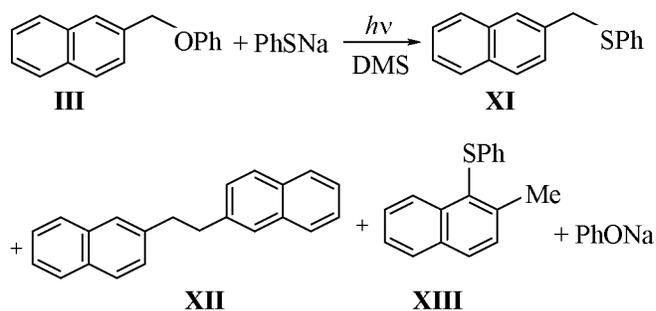
Compd. no.	Irradiation time, min					
	15	30	60	90	120	180
III	78.7	66.0	50.6	40.3	36.2	32.5
XI	15.5	23.8	32.6	36.3	35.5	29.4
XII	4.7	7.7	12.6	15.6	18.5	26.6
XIII	1.1	2.5	4.2	7.8	9.8	11.5

The thiophenolate ion attacks the naphthylmethyl radical both at the benzyl position to yield compound **XI**, and at the aromatic ring affording substance **XIII**. Since the latter cannot form in a common nucleophilic substitution, its presence is another evidence of participation of free radicals as reaction inter-

Scheme 3.



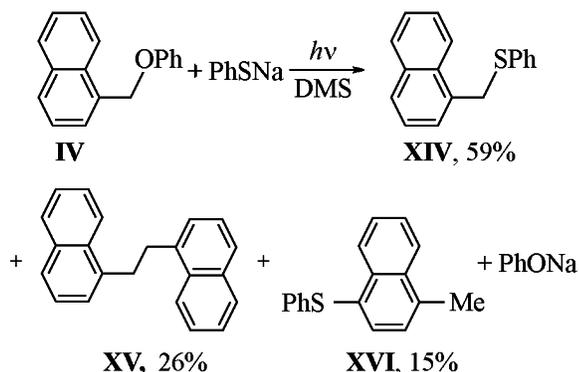
Scheme 4.



mediates. The large amounts of dimer **XII** originate from the increased possibility of radicals recombination with growing stability and stationary concentration of free radicals.

It was remarked earlier [3–5] that anion radicals with a thiophenoxy group in the benzyl position also were capable of fragmentation. This is supported by the character of changes in reaction products composition with duration of the process (Table 1). At the start of the reaction accumulates compound **XI**. Further due to reversibility of its formation its concentration decreases, and as a result arises the stable dimer **XII**. 1-Naphthylmethyl phenyl ether (**IV**) reacts with thiophenolate ion in a similar way (Scheme 5), and the composition of the reaction products is also well consistent with the mechanism under consideration.

Scheme 5.



The reaction rate grows in the series $\text{I} < \text{II} < \text{III} < \text{IV}$. Within 90 min the conversion of the initial ethers amounts to 33, 54, and 60% for ethers **I**, **II**, and **III** respectively. This reactivity series is in agreement with the relative stability of anion-radicals characterized by the LUMO energy values of the corresponding molecules. The stability of anion-radicals from 2-naphthylmethyl and 1-naphthylmethyl phenyl ethers (**III**, **IV**) is virtually the same. However the concurrent reaction of sodium phenolate performed with equimolar mixture of these substrates resulted in conversion of 63% for ether **IV** and 43% for ether **III** within 40 min. This difference is apparently due to significant difference in stability of 1- and 2-naphthylmethyl radicals. Therefore the fragmentation of anion radical in 1-naphthylmethyl system is more exothermic, and the rate of the reaction should be higher.

It was formerly presumed that different behavior of phenylacetonitrile and naphthylacetonitrile anion

radicals was due to unlike localization of the unpaired electron in the anion radicals [7]. In the former anion radical the lone electron is placed on an antibonding σ -orbital localized predominantly on the cyano group. In the latter case the lone electron is placed on an antibonding π -orbital of the aromatic system. Rossi *et al.* [7] think that in this case no fragmentation can occur. Our results suggest that this is not the main factor affecting the stability of the anion radical. Actually, it is presumable that in the anion radicals of compounds **I–IV** the lone electron is localized on the aromatic system of substrate and not on the leaving group. Nevertheless, the fragmentation occurs in all cases with elimination of a phenoxy anion. Obviously the possibility of fragmentation depends both on the stability of the initial anion radical and on the nucleofugal properties of the leaving group. We have previously concluded from the analysis of relative reactivity in fragmentation reactions of anion radicals of weakly nucleofugal leaving groups that the reactivity thereof changes in the following order: $\text{PhO} > \text{AlkO} > \text{CN}$. At sufficiently high energy of the anion radical, as with $\text{BrC}_6\text{H}_4\text{CH}_2\text{R}$, the fragmentation of cyano group with the lowest nucleofugal properties is possible. For the most stable anion radical sharply increases the selectivity toward the change of the leaving group, and fragmentation is then probable only with relatively labile leaving groups OPh , SPh . It is presumable that similar relation between the anion-radical stability and selectivity toward variation of the leaving groups will be retained also on quantitative level.

EXPERIMENTAL

NMR spectra of compounds were registered from 5% solutions in CDCl_3 and $(\text{CD}_3)_2\text{SO}$ on spectrometer Bruker DPX-300 (300 MHz).

The reactions were carried out in DMSO at photoinitiation (mercury lamp of moderate pressure DRL-400, power 400 W) at 35–40°C. The distance from the lamp to ampules was 30 cm.

The reaction mixtures were analyzed by GLC on chromatograph Chrom-5 (flame-ionization detector, carrier gas argon, flow rate 25 ml/min), equipped with glass columns packed with a carrier Chromaton-N-Super with the following characteristics: (1) 1200 × 3 mm, stationary phase 5% SE-30; (2) 1200 × 3 mm, stationary phase 5% XE-60; (3) 2500 × 3 mm, stationary phase 5% SE-30.

The qualitative analysis was carried out by comparison of products retention times with those of

authentic samples prepared by independent syntheses on several columns of different polarity. The quantitative analysis was carried out by the method of internal reference.

In kinetic measurements was used DMSO of "chemically pure" grade after double distillation in a vacuum (7 mm Hg) on calcium hydride through a Vigreux column. The extraction of reaction products was performed with dichloromethane of "chemically pure" grade.

Sodium thiophenolate was prepared under argon from thiophenol (5% excess) and sodium ethylate in ethanol. The residue after evaporation of ethanol was boiled with hexane (3 ml of hexane per 1 g of sodium thiolate), filtered, and dried in a vacuum.

Reactions of 4-vinylbenzyl phenyl ether (I), 4-phenylbenzyl phenyl ether (II), 1-naphthylmethyl phenyl ether (IV) with sodium thiophenolate at photoinitiation. Precisely weighed portions (0.4 mmol) of substrate, freshly prepared sodium thiophenolate (1 mmol), and internal reference (1,2-diphenylethane, 0.17 mmol) were dissolved in 4 ml of DMSO. A weak flow of argon was passed through the mixture till the reagents dissolved completely (10 min). Into 4 ampules of Pyrex glass were charged 1 ml portions of the solution, and a weak flow of argon was passed through the ampules (~15 ml min⁻¹). Three ampules were sealed and after keeping in a thermostat at 35°C they were irradiated with UV light under constant shaking. With every substrate one ampule remained as control, three others were irradiated. Intermittently the ampules were opened, each time 6 ml of water were added, the reaction products were extracted into dichloromethane (3 × 2 ml). The combined extracts were dried with a little magnesium sulfate and analyzed by GLC. The content of the control ampule was treated in the same way, and the solution was used for comparison. Material balance was over 95%. The results of analyses are listed in Table 2.

Reaction of 2-naphthylmethyl phenyl ether III with sodium thiophenolate at photoinitiation. Precisely weighed portions of substrate (168 mg, 0.7 mmol), freshly prepared sodium thiophenolate (231 mg, 1.75 mmol), and internal reference (1,2-diphenylethane, 54.6 mg, 0.3 mmol) were dissolved in 7 ml of DMSO. Reaction and workup of the reaction mixtures were carried out as described for compounds I-IV. Material balance was over 95%.

In a similar way were carried out reactions of nitriles of 1- and 2-naphthylacetic and 4-biphenyl-

Table 2. The composition of reaction mixtures (mol%) in reactions of ethers I, II, IV with sodium thiophenolate in DMSO at photoinitiation

Initial compd. no.	Reaction products (mol%)	Conversion, %	Time, min
I	V (78), VI (14), VII (8)	33	90
II	VIII (83), IX (16), X (1)	54	90
IV	XIV (59), XV (26), XVI (14)	35	20

acetic acids, of 1- and 2-(methoxymethyl)naphthalene with sodium thiophenolate. Reaction time 3 h, conversion 0%, material balance 99%.

Special experiments showed that compounds I-IV are stable under reaction conditions without photoinitiation, and also at irradiation without nucleophile. Compounds VI, IX, X, XII, XIII, XV, and XVI are stable in the course of reaction. Compounds V, VIII, XI, and XIV are unstable in the presence of the nucleophile.

4-Vinylbenzyl phenyl ether (I) was prepared by procedure [5]. mp 111–112°C (from ethanol) [5]. ¹H NMR spectrum (CDCl₃, δ, ppm): 7.54–7.38 m (4H), 7.36–7.23 m (2H), 7.09–6.92 m (3H), 6.76 d.d (1H, ³J_{HH} 10.9, 17.5 Hz), 5.79 d (1H, ³J_{HH} 17.5 Hz), 5.29 d (1H, ³J_{HH} 10.5 Hz), 5.08 s (2H).

4-Phenylbenzyl phenyl ether (II) was prepared along the common procedure for synthesis of ethers of ArCH₂OAr type. To a solution of sodium phenolate obtained by short heating to 90°C of 1.128 g (12 mmol) of phenol and 0.48 g (12 mmol) of NaOH powder in 20 ml of DMSO till complete dissolution of the solid was added in one portion 2.41 g (10 mmol) of 4-bromomethylbiphenyl [8]. In 30 min the reaction mixture was poured into 100 ml of 1% water solution of NaOH. The precipitate was filtered off. Yield 78%, mp 117–118°C (from ethanol). Found, %: C 87.63; H 6.09. C₁₉H₁₆O. Calculated, %: C 87.66; H 6.19. The other ethers and their thioanalogs were also obtained along this procedure.

2-Naphthylmethyl phenyl ether (III) was prepared from 2-bromomethylnaphthalene [9] and sodium phenolate. Yield 68%, mp 119–120°C (from ethanol) [10]. ¹H NMR spectrum (CDCl₃, δ, ppm): 7.96–7.82 m (4H), 7.62–7.46 m (3H), 7.39–7.26 m (2H), 7.11–6.95 m (3H), 5.26 s (2H).

1-Naphthylmethyl phenyl ether (III) was prepared from 1-chloromethylnaphthalene [9] and sodium

phenolate. Yield 78%, mp 74–75°C (from ethanol) [11]. ^1H NMR spectrum (CDCl_3 , δ , ppm): 8.11 d (1H, $^3J_{\text{HH}}$ 8.8 Hz), 7.96–7.87 m (2H), 7.68–7.46 m (4H), 7.41–7.34 m (2H), 7.15–7.02 m (3H), 5.56 s (2H).

4-Vinylbenzyl phenyl sulfide (V) was prepared by procedure [5]. mp 80–81°C (from ethanol) [12]. ^1H NMR spectrum (CDCl_3 , δ , ppm): 7.42–7.15 m (9H), 6.71 d.d (1H, $^3J_{\text{HH}}$ 17.6, 11.9 Hz), 5.74 d (1H, $^3J_{\text{HH}}$ 17.6 Hz), 5.25 d (1H $^3J_{\text{HH}}$ 11.9 Hz), 4.12 s (2H).

(4-Phenylsulfonylmethyl)biphenyl (VIII) was obtained from 4-bromomethylbiphenyl [8] and sodium thiophenolate. Yield 80%, mp 127–128°C (from ethanol). Found, %: C 82.41; H 5.77. $\text{C}_{19}\text{H}_{16}\text{S}$. Calculated, %: C 82.57; H 5.83.

1,2-Bis(4-phenylphenyl)ethane (IX) was obtained by boiling of 4.82 g of 4-bromomethylbiphenyl and 0.5 g of sodium in 50 ml of octane for 4 days. Yield 41%, mp 200–202°C (from ethanol) [13].

4-Methylbiphenyl (X) was prepared by procedure [14]. Yield 20%, mp 51°C (from methanol).

(2-Phenylsulfonylmethyl)naphthalene (XI) was obtained from 2-bromomethylnaphthalene [9] and sodium thiophenolate. Yield 69%, mp 102–103°C (from ethanol). ^1H NMR spectrum (CDCl_3 , δ , ppm): 7.89–7.75 m (3H), 7.71 s (1H), 7.56–7.44 m (3H), 7.40–7.17 m (5H), 4.31 s (2H). Found, %: C 81.51; H 5.71. $\text{C}_{17}\text{H}_{14}\text{S}$. Calculated, %: C 81.56; H 5.64.

1,2-Di(2-naphthyl)ethane (XII) was obtained along procedure [11]. Yield 52%, mp 181–182°C (ethanol-chloroform, 1:1) [11]. ^1H NMR spectrum (CDCl_3 , δ , ppm): 7.89–7.78 m (6H), 7.69 s (2H), 7.53–7.38 m (6H), 3.22 s (4H).

2-Methyl-1-phenylsulfonylnaphthalene (XIII) was obtained by heating for 5 h to 250°C of a mixture containing 8.5 g of 1-bromo-2-methylnaphthalene [9] and 16 g of lead thiophenolate acetate [15]. To the reaction mixture was added 100 ml of toluene, the mixture was heated to boiling, cooled, the precipitate was filtered off, the solvent was distilled off, and the residue was distilled in a vacuum. Yield 57%, bp 145°C (0.3–0.5 mm Hg), n_D^{20} 1.6825, publ. bp 163–165°C (0.7 mm Hg), n_D^{23} 1.6800 [16]. Colorless thick oily substance. ^1H NMR spectrum (CDCl_3 , δ , ppm): 8.57 d (1H, $^3J_{\text{HH}}$ 8.8 Hz), 7.95–7.83 m (2H), 7.59–7.44 m (3H), 7.21–6.91 m (5H), 2.70 s (3H).

(1-Phenylsulfonylmethyl)naphthalene (XIV) was obtained from 1-chloromethylnaphthalene and sodium

thiophenolate. Yield 77%, mp 72–73°C (from ethanol) [17]. ^1H NMR spectrum (CDCl_3 , δ , ppm): 7.89–7.75 m (3H), 7.71 s (1H), 7.56–7.44 m (3H), 7.40–7.17 m (5H), 4.31 s (2H).

1,2-Di(1-naphthyl)ethane (XV) was prepared by method [11]. Yield 49%, mp 162–163°C.

4-Methyl-1-phenylsulfonylnaphthalene (XVI) was prepared as compound XIII from 8.5 g of 1-bromo-4-methylnaphthalene. Yield 56%, bp 140°C (0.2–0.4 mm Hg). Colorless thick oily substance. Found, %: C 81.49; H 5.51. $\text{C}_{17}\text{H}_{14}\text{S}$. Calculated, %: C 81.56; H 5.64.

2-Naphthylmethyl methyl ether was prepared as in [18]. Yield 70%, bp 155° (26 mm Hg), 113°C (1.3 mm Hg) [18].

1-Naphthylmethyl methyl ether was prepared as above. Yield 85%, bp 152°C (27 mm Hg), 106–107°C (3 mm Hg) [19].

2-Naphtylacetic acid nitrile was prepared by heating to 60°C for 2 h of 3.315 g (15 mmol) of 2-bromomethylnaphthalene in 30 ml DMSO with 1.27 g (19.5 mmol) of powdered KCN. On diluting with water (100 ml) the precipitate was filtered off and recrystallized from hexane-chloroform (1:1) mixture. Yield 72%, mp 85–86°C [20].

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