

Note

Nucleophilic Substitution Reaction of *p*-Dinitrobenzene by a Carbanion: Evidence for Electron Transfer Mechanism[†]

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On the basis of investigation of cyclic voltammetry, EPR spectroscopy and competition experiments, the nucleophilic substitution reaction of *p*-dinitrobenzene with the sodium salt of ethyl α -cyanoacetate carbanion in dimethyl sulfoxide giving ethyl α -cyano- α -(*p*-nitrophenyl) acetate is shown to take place via the intermediacy of *p*-dinitrobenzene radical anion. The reaction rate goes faster than that between *p*-nitrohalobenzenes and the same sodium salt of ethyl α -cyanoacetate carbanion. There is an evidence for a single electron transfer mechanism.

Keywords single electron transfer, *p*-dinitrobenzene, radical anion, α -cyanoacetate carbanion, retarding effect

Introduction

Single electron transfer in aromatic nucleophilic substitution has attracted much attention in recent years. In addition to the well-known S_{RN}1 mechanism reported by Bunnett,¹ many other activated aromatic systems, *i. e.*, nitroaryl halides, dinitrobenzenes, *etc.*, have been reported to undergo nucleophilic substitution via the intermediacy of their radical anions formed by single electron transfer from negatively charged or neutral nucleophiles to the aromatic substrates.²⁻¹⁰

p-Dinitrobenzene (**1a**) and nitrohalobenzenes are important reagents in aromatic nucleophilic substitution

reactions. It was reported from this laboratory^{11,12} that *o*-nitrochlorobenzene, *o*-nitrobromobenzene, *p*-nitrochlorobenzene, *p*-nitrobromobenzene and *p*-nitroiodobenzene reacted with the sodium salt of ethyl α -cyanoacetate carbanion (**2**) in dimethyl sulfoxide (DMSO) to give the corresponding ethyl α -cyano- α -(*p*-nitrophenyl) acetate (**4**), respectively. Based on EPR spectroscopic evidence for the formation of nitrohalobenzene radical anions,¹³ kinetic study using EPR F/F lock technique and ¹H NMR line broadening effect, it was concluded that the above mentioned reactions proceeded through the intermediacy of the corresponding nitrohalobenzene radical anions **3** and a single electron transfer mechanism proposed can be schematically represented as Scheme 1.

It was reported in the literature that dinitrobenzene reacted with hydroxide ion to give nitrophenol⁶ and with ^tBuO⁻, ^tBuS⁻ and NEt₃ to give the corresponding nucleophilic substitution products⁴ via the intermediacy of dinitrobenzene radical anion formed through single electron transfer between the nucleophiles and dinitrobenzene.

As an extension of this research, the reaction of *p*-dinitrobenzene (**1a**) with **2** as well as the competition experiments between **1a** and *p*-nitrohalobenzenes (**1b—1e**) with **2** in DMSO (Scheme 2) with the aim of seeking further insight into the mechanism were investigated.

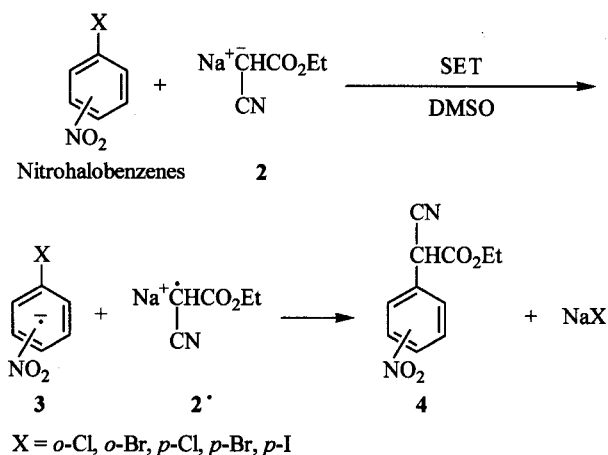
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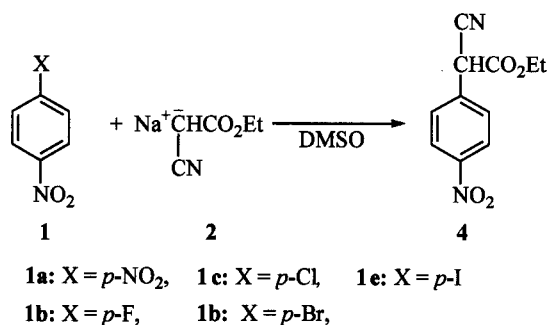
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[†]Dedicated to Professor HUANG Yao-Zeng on the occasion of his 90th birthday.

Scheme 1



Scheme 2



Experimental

Materials

p-Nitrochlorobenzene, *p*-nitrobromobenzene and ethyl α -cyanoacetate were commercial products (A. R.). *p*-Nitrofluorobenzene,¹⁴ *p*-nitroiodobenzene¹⁵ and *p*-dinitrobenzene¹⁶ were prepared according to the literature.

Purification of reagents

Dimethyl sulfoxide (A. R.) was mixed with calcium hydride and the mixture stirred at room temperature for 4 h. It was distilled under reduced pressure (266.64 Pa) and the fraction boiling at 42–43 °C was collected.

Ethyl α -cyanoacetate (A. R.) was dried with magnesium sulfate for 24 h and distilled under reduced pressure (666.6–799.9 Pa) and the fraction boiling at 69–72 °C was collected.

All the nitro compounds were recrystallized from

ethyl acetate.

Preparation of the sodium salt of ethyl α -cyanoacetate carbanion (2)¹⁷

Sodium wire (1.1 g) was dissolved in absolute alcohol (20 mL) and ethyl α -cyanoacetate (5.4 mL) was then added dropwise. A white precipitate was formed, and it was filtered, washed with absolute ethanol and then stored in a vacuum desiccator under argon in the dark.

Cyclic voltammetry

Cyclic voltammetry was performed on a CHI 660 electrochemical apparatus. The electrode potentials of the reactants were determined by cyclic voltammetry in a 0.1 mmol/L solution in DMSO containing 0.1 mol/L ⁿBu₄NClO₄ at a glassy carbon electrode, auxiliary electrode Pt, reference electrode SCE, scan rate: 100 mV/min. Argon was bubbled through the system throughout the determination.

The cyclic voltammogram of *p*-dinitrobenzene (1a) is shown in Fig. 1. The reduction potentials of *p*-dinitrobenzene (1a) and *p*-nitrohalobenzenes (1b–1e) are listed in Table 1.

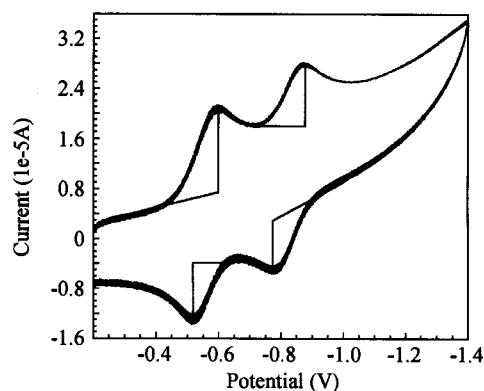


Fig. 1 Cyclic voltammogram of *p*-dinitrobenzene (1a).

Table 1 Reduction potentials of *p*-dinitrobenzene (1a) and *p*-nitrohalobenzenes (1b–1e)

Substrate	1a	1b	1c	1d	1e
E_{red} vs. SCE (V)	-0.601	-1.083	-1.011	-0.998	-0.992

Preparation of ethyl α -cyano- α -(*p*-nitrophenyl) acetate (4)

A solution of *p*-dinitrobenzene (**1a**) (0.60 mmol) in DMSO (2 mL) was mixed with a solution of the sodium salt of ethyl α -cyanoacetate carbanion (**2**) (1.19 mmol) in DMSO (5 mL) and the reaction mixture was bubbled under argon for 10 min and then kept at 90 °C for 1 h. After quenching with dilute hydrochloric acid, the product was isolated by column chromatography to give ethyl α -cyano- α -(*p*-nitrophenyl) acetate (**4**) in yield 93%. ¹H NMR (CDCl₃, Bruker AC-80) δ : 1.26 (t, *J* = 7.1 Hz, 3H), 4.25 (q, *J* = 7.1 Hz, 2H), 4.90 (s, 1H), 7.75 (d, *J* = 8.7 Hz, 2H), 8.33 (d, *J* = 8.6 Hz, 2H). Anal. calcd C₁₁H₁₀N₂O₄: C 56.41, H 4.27, N 11.96; found C 56.48, H 4.25, N 12.24.

EPR experiment

The EPR experiment was carried out on a Bruker 200D-SRC spectrometer equipped with a Bruker ER4111 VT unit to control the reaction temperature at 300 K. The instrument was operated at X-band with 100 kHz modulation and modulation intensity of 0.01 mT, time constant of 0.5 s and microwave power of 10 mW.

Results and discussion

EPR spectrum

When a 0.5 mol/L solution (0.5 mL) of *p*-dinitrobenzene (**1a**) in DMSO was mixed with a 1.50 mol/L solution (0.5 mL) of the sodium salt of ethyl α -cyanoacetate carbanion (**2**) in DMSO in a capillary tube and the mixture deaerated by bubbling under argon for 10 min, EPR study produced a signal as shown in Fig. 2.

Spectral analysis revealed that it was the EPR spectrum for *p*-dinitrobenzene radical anion with *g* = 2.00453, *a_N* = 0.158 mT (2N) and *a_H* = 0.110 mT (4H), in agreement with that reported in the literature.^{4,6}



Fig. 2 EPR spectrum obtained from the reaction of *p*-dinitrobenzene (**1a**) with the sodium salt of ethyl α -cyanoacetate (**2**) in DMSO.

Competitive experiment

The competitive experiment between *p*-dinitrobenzene (**1a**) and *p*-nitrohalobenzene with **2** was carried out as follows: *p*-dinitrobenzene (0.6 mmol), *p*-nitrohalobenzene (0.6 mmol) and the sodium salt of ethyl α -cyanoacetate carbanion (1.2 mmol) were dissolved in DMSO (10 mL) and the reaction mixture was allowed to react at 90 °C for 4 h. The products were separated by column chromatography (SiO₂, petroleum ether/ethyl acetate, 5:1, *V*:*V*). The yields of ethyl α -cyano- α -(*p*-nitrophenyl) acetate (**4**) were calculated as Eq. (1).

The unreacted substrates were recovered, and the results are collected in Table 2.

The results clearly show that *p*-dinitrobenzene has a retarding effect¹⁸ on the reaction of *p*-nitrohalobenzenes in the nucleophilic substitution reaction with **2**.

Conclusion

Based on the EPR signal for the formation of *p*-dinitrobenzene radical anion (**3**), it is evident that the reaction of *p*-dinitrobenzene (**1a**) with **2** to produce ethyl α -cyano- α -(*p*-nitrophenyl) acetate (**4**) takes place via the intermediacy of *p*-dinitrobenzene radical anion. This provides evidence for single electron transfer mechanism. The fact that *p*-dinitrobenzene retards the reaction of *p*-nitrohalobenzenes with **2** is supporting evidence for the mechanism because of its higher reduction potential over that of the latter.¹⁹

$$\text{Yield} = \frac{\text{ethyl } \alpha\text{-cyano-}\alpha\text{-(}p\text{-nitrophenyl)acetate (4) (moles)}}{\text{total amounts of } p\text{-dinitrobenzene plus } p\text{-nitrohalobenzene that have reacted (moles)}} \quad (1)$$

Table 2 Results of competitive experiments of reactions of *p*-dinitrobenzene and *p*-nitrohalobenzene with **2** in DMSO

Entry ^a	Yield of 4		<i>p</i> -Dinitrobenzene recovered		<i>p</i> -Nitrohalobenzene recovered	
	(mg)	(%)	(mg)	(%)	(mg)	(%)
1	108.8	92	35.3	35	67.5	80
2	100.9	90	28.2	28	86.9	92
3	105.7	87	27.2	27	109.0	90
4	104.7	91	31.2	31	130.0	87

^a Entries 1, 2, 3 and 4 represent the reaction systems of *p*-dinitrobenzene (**1a**) with *p*-nitrofluorobenzene (**1b**), *p*-nitrochlorobenzene (**1c**), *p*-nitrobromobenzene (**1d**) or *p*-nitroiodobenzene (**1e**) with **2**, respectively.

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