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Mechanistic investigation on the reaction of 1,1-di-p-substituted phenyl-2,2-dinitroethylene with 1-benzyl-1,4-dihydronicotin-amide in oxygen saturated acetonitrile—clear evidence for intermediate mechanism

Hua-Jian Xu,^a Dan-Mei Dai,^a You-Cheng Liu,^{a,b,*} Jing Li,^a Shi-Wei Luo^a and Yun-Dong Wu^{c,*}

^aDepartment of Chemistry, University of Science and Technology of China, Hefei, Anhui 230026, China ^bNational Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou, Gansu 730000, China ^cDepartment of Chemistry, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

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Abstract—The reaction of 1-benzyl-1,4-dihydronicotinamide with a series of 1,1-di-p-substituted-phenyl-2,2-dinitroethylenes in oxygen-saturated acetonitrile produced various amounts of the corresponding ethanes and diaryl ketones according to the electronic structure of the substituent groups indicating a spectrum of intermediate mechanism between polar mechanism and SET mechanism.

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The mechanism of equivalent hydride transfer from coenzyme NADH models to a variety of substrates has been studied by many investigators and continues to be the area of interest.^{1–11} The focal issue of interest is concerned with the dichotomy into direct hydride (H⁻) transfer (polar mechanism) and multistep electron transfer mechanism, involving electron transfer–proton transfer–electron transfer (e⁻, H⁺, e⁻) or electron transfer–hydrogen atom abstraction (e⁻–H⁻) (SET mechanism). Pross–Shaik theory¹² relates the polar pathway and SET pathway in organic chemistry by Configuration Mixing Model, which implies that the transition states for both processes are likely to be similar. Pross¹³ has discussed the factors governing SET versus polar pathways and indicated that an intermediate mechanism is possible.

Recently, we reported¹⁴ that the reaction of 1,1-diphenyl-2,2-dinitroethylene with 1-benzyl-1,4-dihydronicotinamide (BNAH) proceeds through a transition state of partial diradical and partial covalent bonding character, indicating an intermediate mechanism between polar mechanism and electron transfer mechanism. The idea of partial electron transfer had been suggested before in the literature. Walling¹⁵ first noted that, in the reactions of large activation energy in which single-electron transfer would be expected to be endergonic, it might be considered that charge transfer is only partial in the rate-determining step. Bethell et al.¹⁶ studied the kinetics and mechanism of the reaction of 9-arylfluoren-9-yl cations with polymethylbenzene in trifluoroacetic acid solution and concluded that the overall hydride transfer proceeds through a transition state having considerable electron transfer character and with loosening of the transferred hydrogen. Bunting and Sindhuatmadja¹⁷ studied the kinetics and mechanism of the reduction of 2-methyl and 2-(Z-benzyl)-5-nitroisoquinolinium cation by 1-(X-benzyl)-1,4-dihydronicotinamides and found that the migrating hydrogen atom bears a -0.44 charge in the transition state. Kreevoy et al.¹⁸ reported that the reduction of pyridinium, quinolinium, isoquinolinium, acridinium and other related cations by various 1,4dihydropyridines proceeds via a highly variable transition state structure with different fractional negative charge developing on the migrating hydrogen atom. Hoz and co-workers¹⁹ reported that, in any transition

^{*} Corresponding authors. Tel.: +86 551 3603254; fax: +86 551 3631760 (Y.-C.L.); e-mail: ycliu@ustc.edu.cn

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Figure 1. Compounds 1-6.

state of Michael addition reaction, there is a partial covalent bonding as well as a partial diradical character.

In view of the fact that the oxygen-trapping experiment¹⁴ could produce direct evidence for the diradicaloid character of the transition state in the reaction of BNAH with activated ethylenes, we thought it would be worthwhile to extend the investigation to a series of differently substituted 1,1-diaryl-2,2-dinitroethylenes with the aim of finding the possibility of SET-polar mechanistic spectrum. For this purpose, we have synthesized five 1,1-di-p-substituted-phenyl-2,2-dinitroethylenes (**2**–**6**, mono-p-substituted in the case of **6**) and carried out the reactions of **1**–**6** (Fig. 1) with BNAH in oxygen-saturated acetonitrile and analyzed the products by GC-MS spectroscopy. Herein, we wish to report the results.

Compounds 1–6 were prepared according to the literature.²⁰ 1-Benzyl-1,4-dihydronicotinamide (BNAH) was prepared as described.²¹ A flask containing compounds 1–6 (0.05 mmol) and BNAH (0.05 mmol) was blown with dry oxygen for 10 min, another flask containing dry acetonitrile was bubbled with dry oxygen for 10 min. A portion (5 ml) of the dry acetonitrile was taken and added to the former flask. The reaction vessel was then sealed and allowed to stand under oxygen at room temperature in the dark for corresponding time listed in Table 1. Hydrochloric acid (0.1 M, 1 ml) was added, the mixture was extracted with chloroform and the combined extract dried with Na₂SO₄. After evaporation of the solvent, the residue was subjected to chromatography on a silica gel column with chloroform as eluent, and the pyridinium salt formed and unreacted BNAH was retained on the column. The products were then analyzed by GC–MS spectroscopy (see supplementary information).

In general, substrates with electron withdrawing p-substitutents require shorter reaction times. The reaction times were chosen so that the reactions gave high overall yields. For each reaction, there are two major peaks, which are well separated. They correspond to the reduction product 7 and the oxidation product 8 (Scheme 1).

Table 1. The molar ratios of 8 to 7 from the reactions of 1-6 with BNAH in O₂-saturated acetonitrile

	1	2	3	4	5	6
Х	Н	CH ₃	CH ₃ O	F	Cl	NO ₂
Y	Н	CH_3	CH ₃ O	F	Cl	Н
Reaction time	2.5	4.0	4.5	2.5	2.0	1.5
Overall yields	92	91	90	94	96	98
Retention time of 8 (min)	7.53	10.20	13.56	7.03	11.32	11.67
Retention time of 7 (min)	10.89	12.82	15.56	10.59	14.56	15.72
8:7 (molar ratio)	0.62	0.37	0.36	0.82	0.88	0.53





Scheme 2.

The more polar product 7 has a longer retention time than 8. The differences in retention times are over 2 min. The analytical results are listed in Table 1.

For each reaction, the reduction product 7 was dominant. But the oxidation product 8 was also formed to a considerable extent. By reference to our previous report¹⁴ and the work of Hoz,¹⁹ it is plausible to propose that the reactions of BNAH with 1–6 in oxygen-saturated acetonitrile take place via a concerted electron transfer-hydrogen atom transfer mechanism, schematically represented as shown in Scheme 2.

It is well documented that the reaction of benzylic radicals with oxygen is diffusion controlled,²² so the formation of **8** may be taken as a quantitative measure of the extent of diradical character of the transition state. From the data listed in Table 1, it is seen that the relative amount of ketone increases in the order of MeO < Me < NO₂ < H < F < Cl as the p-substituent group changes in the series. This order is, except for the NO₂, in consistence with the electron withdrawing power of the substituent groups.

A plot of the relative amount of diaryl ketones versus Hammett σ^{023} of the substituents is shown in Figure 2.

In order to rationalize the results, a potential energy surface diagram is constructed as shown in Figure 3 by reference to the potential energy surface diagram given in Ref. 13.

Since EWG substituents increase the rate of reaction, TS will be relatively early (the perpendicular arrow head



Figure 2. Hammett plot for the molar ratio 8:7 versus σ^0 .



Figure 3. Potential energy surface diagram for the reaction of NADH model with compounds 1–6. Line (a) represents concerted hydride transfer mechanism (polar mechanism), in which electron transfer and hydrogen atom transfer with the formation of a C–H covalent bond take place in complete concertedness; line (b) represents an intermediate mechanism in which electron transfer and covalent bond formation are not in complete concertedness, electron transfer has progressed further than hydrogen atom transfer, and the transition state is of partial diradical and partial covalent bonding character; line (c) represents electron transfer mechanism.

moving closer to the upper left corner in Fig. 3), and there should be more oxygen trapping product; while EDG substituents decrease the rate of reaction, the TS will be relatively late and there should be less oxygen trapping product. These are borne out by experiments.

A special note must be made as regards the NO₂ group. NO₂ is known to be a substituent group with a low LUMO orbital,²⁰ which can effectively stabilize a radicaloid species by delocalizing the spin all over the group. Thus, albeit compound **6** reacted with BNAH with the fastest rate among the compounds studied, the yield of **8** from the reaction in oxygen-saturated acetonitrile was of medium value (Table 1).

In conclusion, the experimental results reported provide clear evidence for the fact, due to the electronic effect and steric effect of the substrate molecules, there exists a mechanistic spectrum of intermediate mechanism between polar mechanism and SET mechanism in the title reaction of BNAH with activated ethylenic compounds.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2005. 06.095.

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