

THE MECHANISM OF NUCLEOPHILIC SUBSTITUTION IN HALOPYRYLIUM AND HALOBENZOPYRYLIUM SALTS

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The electrochemical behavior of 4-chloro-2,6-diphenylpyrylium and 4-chloro(bromo)flavylium perchlorates has been studied. Their reaction with nucleophiles has also been studied. It was shown that nucleophilic substitution in these compounds occurs through a stage of forming a charge-transfer complex which passes into an ion-radical pair as a result of a one-electron transfer. Heterolytic fission of the C-Hal bond occurs at the stage of the radical or adduct of the substituted pyrylium (flavylium) salt and nucleophile.

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Reactions of electrophilic and nucleophilic substitution in aromatic compounds are key reactions in organic chemistry and because of this their mechanisms have been fairly well studied. The scheme of electrophilic substitution is classical, comprising the sequential formation of π, σ, π -complexes. In addition theoretical and experimental data have appeared indicating the more complex character of this process. Considerations on the possibility of one further stage, electron transfer, preceding the formation of the σ -complex [1], were confirmed almost forty years later [2]. The stage indicated in the nitration reaction was demonstrated experimentally for a series of aromatic compounds (such as naphthalene) and also for heterocyclic substrates (benzodioxine and phenoxazine) [3,4].

The mechanism of nucleophilic substitution reactions in aromatic compounds from the position of one-electron transfer has been considered in only a few studies [5,6]. This is possibly connected with the lower ability of nucleophilic substitution in aromatic compounds to be studied compared with electrophilic substitution. In the chemistry of heterocyclic compounds nucleophilic substitution reactions are fairly widespread and lead to interesting results but regrettably their mechanism is also little studied. The reaction of halogen-substituted pyrylium and flavylium salts with various nucleophiles is a convenient subject for studying the mechanism of similar reactions.

Selection of the models indicated was not accidental. The process of pyrylium cations reduction has been fairly well studied by physicochemical methods and preparatively [6-9]. At the preparative level nucleophilic substitution has been considered both for γ -unsubstituted and for γ -halogen substituted pyrylium cations [10-12]. The authors showed that in the first case the pyrylation reaction goes through the stage of the 4H-pyran formation with subsequent fission of hydride ion. It is considered proven that the "formal hydride fission" reaction is a one-

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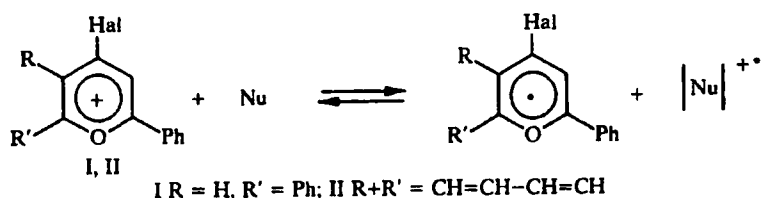
TABLE 1. Electrochemical Characteristics of the Model Compounds*

Compound	Primary		Secondary			I_{pa}/I_{pc}
	E'_{pc} , V	E''_{pc} , V	E'_{pa} , V	E''_{pa} , V	E'''_{pa} , V	
4-Chloro-2,6-diphenylpyrylium perchlorate	-0.2	-1.1	—	—	1.4	0.8
4-Chloroflavylium perchlorate	-0.2	-0.96	-0.60	0.05	1.0	0.8
4-Bromoflavylium perchlorate	-0.1	-0.85	-0.05	0.80	1.1	0.9

* E'_{pc} and E_{pa} are the potentials of reduction and oxidation at the platinum electrode relative to a saturated silver chloride electrode in acetonitrile. Operating solution concentration $5 \cdot 10^{-3}$ M, potential scanning rate 0.5 V/sec.

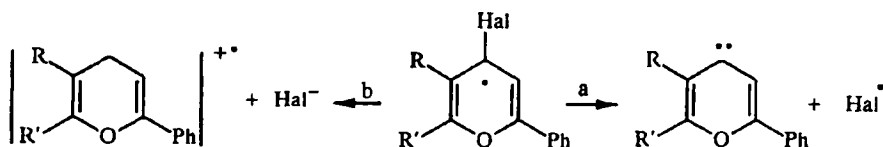
electron process [13] and it may therefore be suggested that an analogous process also takes place in the pyrylation reaction (and possibly in heterylation).

In the general form the following scheme may be representative for halogen-substituted pyrylium (I) and flavylium (II) derivatives.



We synthesized 4-chloro-2,6-diphenylpyrylium, 4-chloro- and 4-bromoflavylium perchlorates and reduced them electrochemically in order to solve the problem of the mechanism of rupture of the C-Hal bond (Table 1). Two routes are possible for the subsequent conversion of the resulting radical, viz. (a) homolytic and (b) heterolytic.

In the case of homolysis the formation of a pyranyl (flavanyl) biradical and a Hal radical might be expected.



On heterolytic rupture of the C-Hal bond a pyranyl (flavanyl) cation-radical and Hal- anion may be formed.

It is seen from the data of Table 1 that chlorodiphenylpyrylium cation on reduction forms an unstable radical (there is no anode peak at a potential scanning rate of 0.5 V/sec). Chloro- and bromo-substituted flavylium cations form more stable radicals in the first stage of reduction due to the delocalization of the unpaired electron

TABLE 2. Spectrophotometric, Kinetic, and Electrochemical Data on the Reaction of Halogen-Substituted Cations with N,N-Dimethylaniline (1:1)*

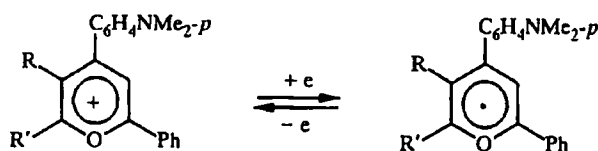
Cation	λ_0 , nm	λ_1 , nm	λ_2 , nm	$-E_{pc}$, V	k, M ⁻¹ ·sec
4-Chloro-2,6-diphenylpyrylium	290	370	530	0.6	0.2
4-Chloroflavylium	300	350	580	0.46	0.55
4-Bromoflavylium	300	350	580	0.46	3.1

* λ_0 is for the initial substrate, λ_1 and λ_2 for the products.

along the condensed aromatic system. For all studied cations in the secondary branches of the cyclic voltamperograms peaks of the halide anions (Cl^- and Br^-) oxidation were observed [14] and identified by the behavior of added tetrabutylammonium chloride and bromide. Consequently reduction of halogen-substituted pyrylium and flavylium cations leads to fragmentation of the resulting halogen-substituted pyranyl and flavanyl cations by fission of halide anion.

N,N-Dimethylaniline was used as nucleophilic reagent when examining the mechanism of an actual nucleophilic substitution reaction. The stoichiometry and kinetics of this process were studied by the electrochemical method using cyclic voltamperograms. It became clear that the substrate and reagent react at a 1:1 ratio which confirmed once again the fission of halogen as anion from the pyranyl radical. The stoichiometric ratio of substrate to reagent must be 1:2 for removal of the halogen as a radical (Hal^\cdot). All the reactions examined were described by kinetic equations of the second order (first order with respect to each of the reactants).

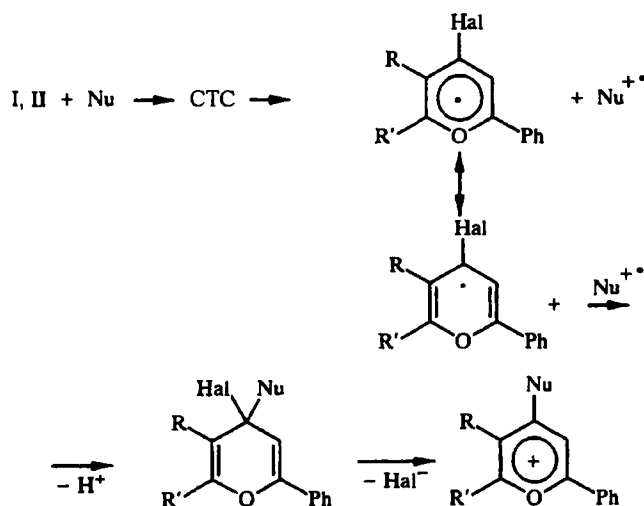
The nature of the halogen and the presence of a condensed benzene ring affects the rate of reaction of halogen-substituted pyrylium and flavylium cations (Table 2). Nucleophilic substitution occurs more readily with 4-bromoflavylum perchlorate. We synthesized 4-(N,N-dimethylaminophenyl)-2,6-diphenylpyrylium perchlorate by the method described in [12] to identify the final product of nucleophilic substitution. This salt was used as a standard compound in the electrochemical reaction between 4-chloro-2,6-diphenylpyrylium perchlorate and N,N-dimethylaniline. Reaction of the model cations with N,N-dimethylaniline leads to the product of nucleophilic substitution in the initial salts, which are capable of reverse addition of one electron leading to the formation of stable radicals.



The presence of a one-electron transfer stage in nucleophilic substitution of halogen-substituted pyrylium cations was confirmed by ESR (Fig. 1). On dissolving the chloroflavylum salt in dimethylaniline at 77 K a superposition of the spectra of the chloroflavylum radical and the dimethylaniline cation-radical was observed.*

The generation of a charge transfer complex (CTC) recorded spectrophotometrically (Table 2, value of λ_1) precedes the formation of an ion-radical pair.

The data obtained enable the nucleophilic substitution of halogen in cations I and II to be described by the following scheme.



*The experiment using ESR was carried out by A. I. Prokofev (Institute of Elementorganic Compounds, Russian Academy of Sciences).

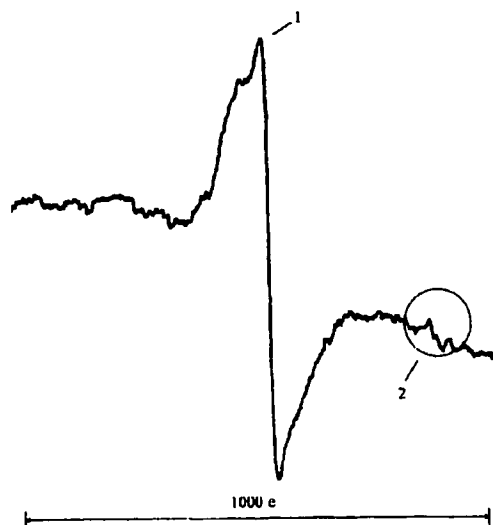


Fig. 1. Superposition of ESR spectra of the haloflavylium radical and the dimethylaniline cation-radical at 77 K:
 1) dimethylaniline cation-radical; 2) chloroflavylium radical.

We therefore propose that nucleophilic substitution in halogen-substituted pyrylium and flavylium salts passes through a stage of forming a charge-transfer complex which is converted into an ion-radical pair by one electron transfer. Heterolytic fission of the C–Hal bond occurs at the stage of the radical or the adduct from the reaction of the pyrylium salt and nucleophile.

EXPERIMENTAL

An electrochemical system with programming provision was used for carrying out the series of electrochemical experiments (Pi-50 potentiostat, PR 8 programmer). Calculation of the electrons recorded in the experiments was carried out with a standard substance (ferrocene).

A three-electrode cell of operating volume 3 ml linked to the potentiostat was used for taking the cyclic voltamperograms. A platinum electrode of surface area 3.14 mm^2 was used as the operating electrode. The reference electrode was a saturated silver chloride with a water-impermeable diaphragm. The auxiliary electrode was platinum. Tetrabutylammonium perchlorate Bu_4NClO_4 (0.1 M) was used as base electrolyte. It was recrystallized twice from an acetylacetone–pentane mixture with subsequent drying at 100°C in a vacuum chamber for 48 h. Acetonitrile was purified by the procedure described in [13]. Deaeration was effected with argon. Electronic absorption spectra were taken with a SF-46 spectrophotometer, wavelength range 200–750 nm at 10 nm intervals. Thickness of the absorption layer was 10 mm. The reference solution was aceto-nitrile. Operating solution was $5 \cdot 10^{-3}$ M. The ESR spectra were recorded on a Varian E-12A radio-spectrometer.

4-Chloro-2,6-diphenylpyrylium perchlorate was synthesized from 2,6-diphenyl- γ -pyranone and PCl_5 by the method described in [15]. 4-(N,N-Dimethylaminophenyl)-2,6-diphenylpyrylium perchlorate was synthesized from 4-chloro-2,6-diphenylpyrylium perchlorate and N,N-dimethylaniline by the known procedure of [12].

4-Chloro- and 4-bromoflavylium perchlorates were obtained from flavone and PCl_5 or PBr_5 respectively as described previously in [15].

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