KINETIC INVESTIGATION OF CYCLIZATION OF 1-ACETYL-1'-(X-CINNAMOYL)FERROCENES

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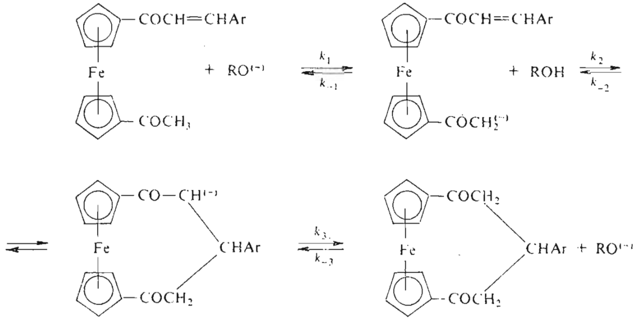
Ten substituted 1-acetyl-1'-(X-cinnamoyl)ferrocenes were prepared and the kinetics of their cyclization to 3-aryl[5]ferrocenophane-1,5-diones was investigated. Cyclizations are the first order reactions with respect to the starting compounds $\Delta H^{\neq} \sim 85$ kJ mol^{-1} and $-\Delta S^{\neq} \sim 40$ to 60 J mol^{-1}. The log k well correlated with σ constants, and ϱ (0·83) is virtually temperature independent in the studied 35–55°C interval.

Our preceding papers dealt with the kinetics of addition of ethyl cyanoacetate to substituted cinnamoylferrocenes[1] or 1-benzoyl-1'-(X-cinnamoyl)ferrocenes[2], and also with additions of ethyl 2-cyanobutanoate to substituted cinnamoylferrocenes[3]. Good correlations of rate constants with Hammett σ constants were found with all these compounds. The kinetics of cyclization of 1-cinnamoyl-1'-(X-phenylacetyl)-ferrocenes was examined and found[4] that the reaction rate considerably depends on the polar effects of substituents upon the active component of the Michael addition. Recently also the dependence of activation parameters of cyclization on the ring size formed was studied[5].

This paper was aimed to investigate the kinetics of cyclization of 1-acetyl-1'-(X-cinnamoyl)ferrocenes and to ascertain whether the polar substituent effects at the acceptor of the Michael addition will be differently manifested with intra- and intermolecular processes.

1-Acetyl-1'-(X-cinnamoyl)ferrocenes were prepared by a Friedel–Crafts acetylation of substituted cinnamoylferrocenes with acetyl chloride under catalysis of $AlCl_3$. No attention was paid to the optimization of yields. The structure of products was supported by ^{1}H NMR spectra of some derivatives; all measured compounds revealed, in addition to chemical shifts of cinnamoylferrocenes[6], a singlet of acetyl group at $\delta = 2·83$ ppm, the position of which does not depend on the nature of the substituent. The IR spectrum showed two maxima in the carbonyl band region: that at 1 680 cm^{-1} is substituent independent and can be ascribed to the acetyl group. The second one at 1 660 cm^{-1} is associated with the cinnamoyl moiety and is substituent dependent. Since the $\Delta\nu$(CO) is rather small (8 cm^{-1}) no attempt to correlate it with σ constants was made.

The cyclization course of 1-acetyl-1′-(X-cinnamoyl)ferrocene can be illustrated as in Scheme 1. At the beginning of the kinetic study it was necessary to clarify whether the observed rate constant calculated by the Guggenheim method for monomolecular reactions characterizes the pure cyclization step (k_2), or, whether it also comprises a preceding acid–base equilibrium, *i.e.* k_1 and k_{-1}. Investigation of dependence of log k upon the log $[CH_3ONa]$ (the catalyst) (Fig. 1) showed this dependence to be linear in the 0·5 to 25 mmol dm^{-3} range with the line slope 1·39 at 39°C ($r = 0{\cdot}998$) and 1·22 at 52°C ($r = 0{\cdot}997$). The equilibrium concentration



SCHEME 1

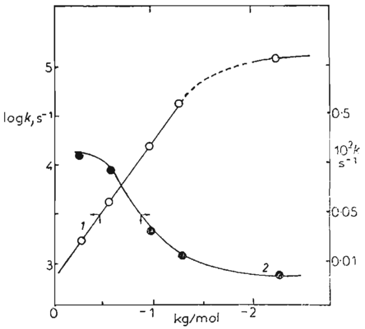


FIG. 1

Relationships: logarithm of rate constants (curve *1*), or rate constants (curve *2*) upon logarithm of the catalyst concentration of the carbanion depends, at the acid–base equilibrium, on the concentration of the catalyst (a base). The already mentioned dependence seems to approach the limit at higher concentrations of the catalyst. Since we worked in this very range and used the same concentration of methoxide ions in all measurements, it can be anticipated that the carbanion concentration is constant; due to the great distance of the substituent from the —$COCH_3$ group the equilibrium should be substituent independent. That means that the measured rate constants express the cyclization with a constant contribution of the acid–base equilibrium for all derivatives. Plateau observed in the low concentration region of the catalyst (5 mmol dm^{-3}) indicates that the reaction might also be acid catalyzed.

Results of the kinetic studies are summarized in Table I. The activation enthalpy ($\Delta H^{+} = 85$ kJ mol^{-1}) is very little substituent dependent. A little more significant dependence on the substituent was seen with the activation entropy, where $-\Delta S^{+}$ varies from 40 to 60 J mol^{-1} K^{-1}. Thus, the intramolecular process requires an approximately double activation enthalpy and less than a half of the activation entropy, as follows from comparison of ΔH^{+} and ΔS^{+} of the intramolecular Michael addition under investigation with an analogous intermolecular process[3] (addition of ethyl 2-cyanobutanoate to chalcones). This is caused by a different number of the freedom degree, which the reactants have at an intermolecular and intramolecular process in the starting or, above all, in transition states.

Since the reaction rate was significantly influenced by the substituents, the validity of the isokinetic relation was studied for the given reaction series according to[7]. From the values of standard deviation $s_0 = 0{\cdot}042$, $s_{\infty} = 0{\cdot}043$, $s_s = 0{\cdot}044$, $s_{\infty} = 0{\cdot}044$, $s_R = 0{\cdot}360$, $s_T = 0{\cdot}24$, we suggest that a homogeneous isoenthalpic series with $T = -535$ K was involved. Since the homogeneous reaction series is concerned, we were entitled to construct the dependence $\log k = \varrho\sigma + c$, the results of which are listed in Table II. It is obvious that in the studied temperature range the line slope of the given relationship is virtually constant, what is in agreement with results obtained with an intermolecular Michael addition[3]. A greater deviation of this relationship was observed at 45°C (0·731 when contrasted with the mean values of other line slopes 0·828). This is caused by a point due to the *p*-Cl derivative.

Comparison of ϱ constants of these cyclizations ($\varrho = 0{\cdot}83$) with those obtained with addition of ethyl 2-cyanobutanoate ($\varrho = 0{\cdot}67$), or ethyl cyanoacetate[1] ($\varrho = 0{\cdot}65$) upon the substituted cinnamoylferrocenes, as well as with ϱ constant of addition of ethyl cyanoacetate to 1-benzoyl-1′-(X-cinnamoyl) ferrocenes[2] ($\varrho = 0{\cdot}67$) showed that: *1*) The Michael addition to substituted cinnamoylferrocenes is little sensitive towards the character of the nucleophile (ethyl cyanoacetate $\varrho = 0{\cdot}65$, 2-ethyl-2-cyanobutanoate $\varrho = 0{\cdot}67$); *2*) Sensitivity of the Michael addition to polar effects of substituents increases with the rise of the electron accepting properties of a group activating the multiple bond.The $\varrho = 0{\cdot}65$ for addition of ethyl cyanoacetate to substituted cinnamoylferrocenes and 0·76 for addition to 1-benzoyl-1′-(X-cinnamoyl)-

TABLE I

Kinetic parameters of cyclization of 1-acetyl-1′-(X-cinnamoyl)ferrocenes

Compound	λ, nm	log ε	λ, nm	log ε	$10^5 . k_{35}{}^a$	$10^4 . k_{40}{}^a$	$10^4 . k_{45}{}^a$	$10^4 . k_{50}{}^a$	$10^4 . k_{55}{}^a$	$\Delta H^{\ddagger}$ KJ mol^{-1}	$\Delta S^{\ddagger}$ J mol^{-1} K^{-1}
I	342	4·081	222	4·036	7·521	1·275	2·221	3·755	5·645	85·62 ± 1·89	−54·36 ± 1·62
II	317	4·424	223	4·370	6·368	1·220	1·864	3·149	4·755	83·29 ± 3·00	−62·94 ± 3·12
III	307	4·154	222	4·165	7·886	1·511	2·826	4·222	6·312	87·03 ± 5·08	−48·79 ± 3·81
IV	307	4·183	223	4·236	9·396	1·626	2·590	5·052	5·956	80·94 ± 6·58	−67·47 ± 7·51
V	301	4·346	250	4·244	9·706	1·454	2·935	4·229	6·743	82·81 ± 4·48	−61·63 ± 4·53
VI	311	4·173	223	4·163	11·535	2·204	3·800	6·179	11·677	94·77 ± 2·48	−21·05 ± 0·71
VII	312	4·239	223	4·201	12·408	2·439	4·450	7·339	9·547	87·01 ± 6·73	−44·95 ± 4·56
VIII	298	4·427	223	4·468	18·875	3·047	6·107	9·738	13·455	85·59 ± 5·32	−46·80 ± 3·79
IX	300	4·095	220	4·474	19·075	3·355	4·619	10·020	14·034	85·37 ± 6·18	−47·65 ± 4·50
X	305	4·373	222	4·298	40·335	6·710	9·148	19·620	30·070	85·38 ± 6·35	−41·84 ± 3·95

[a] in s^{-1}.

TABLE II

Characteristics of correlations log k upon σ for the investigated derivatives

Values	35°C	40°C	45°C	50°C	55°C
r	0·951 ± 0·08	0·951 ± 0·08	0·956 ± 0·065	0·952 ± 0·08	0·946 ± 0·08
q	−4·049 ± 0·05	−3·798 ± 0·05	3·559 ± 0·041	−3·339 ± 0·05	−3·172 ± 0·05
ϱ	0·8318 ± 0·096	0·8009 ± 0·092	0·731 ± 0·079	0·8393 ± 0·096	0·8414 ± 0·1

TABLE III

1-Acetyl-1′-(X-cinnamoyl)ferrocenes

Compound X	Formula (mol.weight)	Calculated/Found			M.p., °C yield, %
		% C	% H	% Fe	
I	$C_{22}H_{20}FeO_3$	66·06	5·19	14·38	157–159
4-OCH_3	(388·3)	67·88	5·23	13·91	35
II	$C_{22}H_{20}FeO_2$	70·98	5·42	15·00	132–134
4-CH_3	(372·3)	70·99	5·43	15·11	39
III	$C_{21}H_{18}FeO_2$	70·41	5·06	15·59	131–132
H	(358·2)	70·52	5·12	15·63	54
IV	$C_{21}H_{17}FFeO_2$	67·04	4·55	14·85	135–139
4-F	(376·2)	67·13	4·57	14·76	57
V	$C_{22}H_{20}FeO_2$	68·06	5·19	14·38	137–139
3-OCH_3	(388·3)	67·21	5·22	14·09	29
VI	$C_{21}H_{17}ClFeO_2$	64·23	4·36	14·22	165–167
4-Cl	(392·7)	64·55	4·42	14·10	34
VII	$C_{21}H_{17}BrFeO_2$	57·70	3·92	12·78	169–171
4-Br	(437·1)	57·13	3·89	12·62	54
VIII	$C_{21}H_{17}ClFeO_2$	64·23	4·36	14·22	144–146
3-Cl	(392·7)	64·20	4·40	14·31	37
IX	$C_{21}H_{17}BrFeO_2$	57·70	3·92	12·78	134–136
3-Br	(437·1)	56·96	3·78	12·64	41
X	$C_{22}H_{17}FeNO_2$	68·85	4·47	14·57	205–207
3-CN	(383·2)	68·55	4·50	14·55	42

ferrocenes. Analogously, $\varrho = 0{\cdot}67$ for addition of ethyl 2-cyanobutanoate to substituted cinnamoylferrocenes. $\varrho = 1{\cdot}05$ for addition of the same reagent to similarly substituted benzene chalcones ($\varrho = 1{\cdot}05$); (ferrocenyl is a much stronger electron donor than phenyl); *3*) The examined cyclization of 1-acetyl-1 -(X-cinnamoyl)-ferrocenes, which is an intramolecular addition ($\varrho = 0{\cdot}83$) is by 10% more sensitive towards polar effects of substituents than the intermolecular one ($\varrho = 0{\cdot}76$). A relatively large slope, expressing the influence of polar effects of substituents at the donor of additions on the reaction rate was reported[4] for cyclization of 1-cinnamoyl-1'-(X-phenylacetyl)ferrocenes. This is probably due to a preceding acidobase equilibrium. The substituent might influence the thermodynamic stability and consequently, also the concentration of the nucleophile (—COCHAr) in that case.

EXPERIMENTAL

Acetylation of Cinnamoylferrocenes

Acetyl chloride (2·5 mmol) was added to a stirred solution of a substituted cinnamoylferrocene[8] (1·7 mmol) in dichloromethane (40 ml) at 0°C. Aluminium chloride (2·8 mmol) was then stepwise added, the mixture stirred at room temperature for 4 h and poured into water. The organic material extracted with dichloromethane was washed with water and dried with Na_2SO_4. The residue after evaporation of the solvent was chromatographed on an Al_2O_3 column, benzene–ethyl acetate 9·5 : 0·5 being the eluent. Products of this reaction (crystallized from benzene–light petroleum) are listed in Table III. The melting points were determined on a Koffler micro hot-stage.

Methods

The digital data-recording system, consisting of a registration spectrophotometer Perkin–Elmer 450, a repetitive scanning accessory for rescan the absorption spectrum and a digital data-recorder Perkin–Elmer DDR-2G, was used for kinetic study. The automated system[9] described a parallel recording of two coordinates, whilst our measurements required scanning of three coordinates; therefore, some modifications have to be made. The measuring system was fully automatic and digital controlled.

The solvent for cyclizations was methanol, concentrations of the sample and sodium methoxide were 0·05 mmol dm^{-3} and 0·5 mol dm^{-3}, respectively. The measured volumes of solutions (2 ml each) were temperated in mixing chambres; sodium methoxide was dosed to the sample containing chamber under pressure and immediatelly transferred into the celll placed in the temperated block of the spectrophotometer. The mixing and the filling of the cell did not last more than 5 s. Since the UV light caused decomposition of the starting material, the irradiation time was restricted to the minimum by inserting an automatically controlled diaphragm in fromt of the cell containing the sample. Measured was the decrease of the starting material in the 305 nm range, where the product revealed no considerable maximum. The absorbance read-out was accurate to ±0·003, temperature of the reaction mixture was kept constant within ±0·1°C and ±0·3°C (in long-time measurements).

Rate constants were calculated according to the Guggenheim[10] method, reaction orders by a differential method for one wavelength at the maximum corresponding to the absorption of the starting material. The programme according to[7] was employed for calculation of the isokinetic relationship. Results of kinetic measurements are listed in Table I.

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