

PDF hosted at the Radboud Repository of the Radboud University Nijmegen

The following full text is a publisher's version.

For additional information about this publication click this link.

<http://hdl.handle.net/2066/107485>

Please be advised that this information was generated on 2018-07-08 and may be subject to change.

EFFECTS OF
SUBSTITUENTS
IN THE
IODINE-CATALYZED
ISOMERIZATION
OF CIS-STILBENE

W. J. MUIZEBELT



EFFECTS OF SUBSTITUENTS
IN THE IODINE-CATALYZED ISOMERIZATION
OF CIS-STILBENE

PROMOTOR: PROF. DR. R.J.F. NIVARD

EFFECTS OF SUBSTITUENTS
IN THE IODINE-CATALYZED
ISOMERIZATION
OF CIS-STILBENE

P R O E F S C H R I F T

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR
IN DE WISKUNDE EN NATUURWETENSCHAPPEN
AAN DE KATHOLIEKE UNIVERSITEIT TE NIJMEGEN,
OP GEZAG VAN DE RECTOR MAGNIFICUS DR. A.J.H. VENDRIK,
HOGLERAAR IN DE FACULTEITEN DER GENEESKUNDE
EN DER WISKUNDE EN NATUURWETENSCHAPPEN,
VOLGENS BESLUIT VAN DE SENAAT IN HET OPENBAAR TE VERDEDIGEN
OP VRIJDAG 5 MEI 1967 DES NAMIDDAGS TE 4 UUR

DOOR

WILLEM JOHAN MUIZEBELT

GEBOREN TE BORNE

1967

THOBEN OFFSET NIJMEGEN

Voor suggesties die tot dit onderzoek geleid hebben zeg ik Prof.Dr. E.C.Kooyman hartelijk dank.

I wish to thank Prof. Dr. R.M.Noyes (University of Oregon, Eugene, Oregon, U.S.A.) for his interest in this study and for helpful discussions.

Mevrouw G.A.v.d.Mey-Hay ben ik veel dank verschuldigd voor het corrigeren van de Engelse tekst van het manuscript.

Aan Ineke

CONTENTS

CHAPTER I: INTRODUCTION	9
I.1 The reaction of halogen atoms with olefins	9
I.2 Halogen atom catalyzed cis-trans isomerization	10
I.3 Iodine atom catalyzed cis-trans isomerization	13
I.4 Objectives and survey of the present study	14
I.5 Notation for the cis- and trans-stilbene derivatives	15
CHAPTER II: EXPERIMENTAL METHODS	17
II.1 Materials used	17
II.2 General measuring procedure	17
II.3 Other procedures	18
II.4 Influence of oxygen	18
II.5 Sealing technique	19
II.6 Influence of light	20
II.7 Spectrophotometric analysis	20
II.8 Accuracy of the measurements	22
II.9 Statistical treatment of the results	24
II.10 U.V. Spectra	25
CHAPTER III: RESULTS	27
III.1 Reaction rate constants	27
III.2 Hammett plots	36
III.3 The dependence of ρ on temperature	37
III.4 Arrhenius activation parameters	38
III.5 Derivation of a general rate equation for meta- and para- substituted cis-stilbenes	42
III.6 Ortho-substituted stilbenes	42
III.7 Uncatalyzed thermal isomerization	44

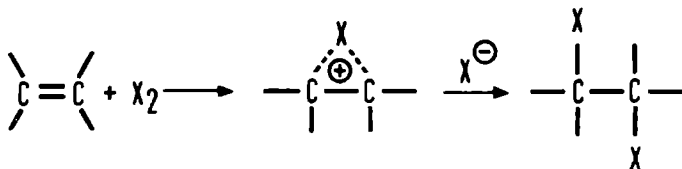
CHAPTER IV: DISCUSSION	47
IV.1 Energy scheme of the reaction	47
IV.2 Effects of substituents	51
A. The inductive effect	52
B. The resonance stabilization of the transition state by para substituents	54
C. The absolute value of ΔE_X^i	58
IV.3 The deviation of C3tBu from the Hammett line	61
IV.4 Iodine-catalyzed cis-trans isomerization of styrylpyridines and cis-stilbene	63
 CHAPTER V: IODINE-CATALYZED ISOMERIZATIONS OF PARA-METHOXY-CIS-STILBENES AT ROOM TEMPERATURE; HIGH ORDER REACTIONS	 65
V.1 Deviations in the behaviour of C4OCH ₃ at high iodine concentrations	65
V.2 Kinetic investigations at room temperature	66
V.3 Mechanism of the reaction.	69
V.4 The influence of complex formation.	75
 CHAPTER VI: SYNTHESSES	 79
VI.1 Reaction scheme	79
VI.2 Benzyl bromides	80
VI.3 Benzaldehydes	81
VI.4 Phenylacetic acids	82
VI.5 Stilbene derivatives	83
 SAMENVATTING	 91
 REFERENCES	 95

CHAPTER I

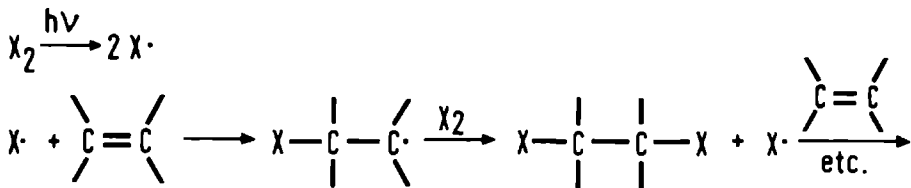
INTRODUCTION

I.1 THE REACTION OF HALOGEN ATOMS WITH OLEFINS

It is well-known that halogens can be added to the double bond of a substituted ethylene to give 1,2-dihalogenated products. The reaction can take place via two essentially different mechanisms. In polar media the reaction occurs mainly via an ionic mechanism:



In the gas phase and in apolar solvents the reaction can also proceed as a radical chain process. Such a reaction mechanism is found under conditions which produce halogen atoms from molecules; e.g. irradiation:



However, in apolar media addition following this mechanism may be overshadowed by heterolytic additions if care is not taken to exclude traces of water or hydrogen halides. Even if the reactants are mixed in the vapour phase the addition may still proceed heterolytically on the glass walls of the container unless these are coated with a non-polar material such as paraffin^{1a}.

Both chlorine and bromine can be added to the double bond but iodine adds only to simple olefins at low temperatures and the reverse process is more readily studied in this case. This can be understood considering the bond strengths of the C-X bonds. According to Walling^{2a} the bond strengths of the carbon-halogen bonds in methyl iodide, bromide and

chloride are 53, 67.2 and 80.6 kcal respectively. For the different steps in the addition of halogens to ethylene the following energetics are given (table I):

T a b l e I
Energetics of chain steps in radical additions of halogens to ethylene^{2b}
(in kcal/mole at 25°C)

X ₂	ΔH_a X· + CH ₂ = CH ₂	ΔH_b ·CH ₂ -CH ₂ X + X ₂	$\Delta H_a + \Delta H_b$
Cl ₂	-26	-19	-45
Br ₂	- 5	-17	-22
I ₂	7	-13	- 6

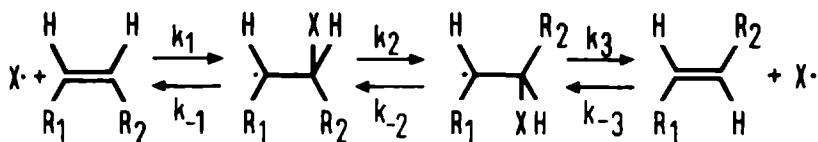
It is seen that the first step is endothermic in the case of iodine, weakly exothermic with bromine and strongly exothermic with chlorine. The overall process of addition of one molecule of halogen to one molecule of ethylene becomes increasingly exothermic in the series I₂ < Br₂ < Cl₂.

The entropy will diminish in the halogen addition reaction since the number of molecules is diminished. Addition of iodine will therefore take place only at low temperatures when energy changes will be most important whereas at higher temperatures entropy changes will control the process and the reverse reaction will occur. Additions of chlorine and bromine are irreversible at ordinary temperatures and the addition of chlorine appears to become reversible only at temperatures above 200°.

I.2 HALOGEN ATOM CATALYZED CIS-TRANS ISOMERIZATION

Although addition of one *molecule* of halogen is only reversible in the case of iodine the first step in this process (the addition of a halogen *atom*) has been found to be reversible in the case of bromine and iodine atoms. This reversibility is most strikingly demonstrated by the ability of bromine and iodine atoms to catalyze cis-trans isomerizations of 1,2-disubstituted ethylenes. It is generally believed that the first step in the halogen atom catalyzed isomerization is also the addition of a halogen atom to the double bond. The double bond has now become single and rotation around this bond has thus become much easier. Dissociation

of the halogen atom from the radical after this rotation step results in the formation of the trans compound:



With chlorine atoms this reaction will be obscured by the concurrent completion of the addition, since the first step is irreversible and further reaction with a chlorine molecule will occur. Nevertheless, it has been found that $\alpha,2,3,4,5,\alpha',2',3',4',5'$ -decachloro-cis-stilbene is converted to the corresponding trans-stilbene under the influence of chlorine and light³. Perhaps the addition of the chlorine atom is reversible for steric reasons in this case.

When bromine atoms are used as a catalyst isomerization reactions are also accompanied by the bromine addition but with iodine the only reaction is generally isomerization and this compound is known as an effective catalyst for cis-trans isomerizations.

If pure cis compound is used as a starting material and the reaction is followed until small conversions there will be only cis-trans isomerization. Trans-cis isomerization can also be neglected if the energy of the trans compound is much lower than that of the cis compound so that the equilibrium $\text{cis} \rightleftharpoons \text{trans}$ lies far to the right. The rate law for cis-trans isomerization is:

$$v = \frac{k_1 k_2 [\text{cis}] [\text{X}\cdot]}{k_{-1} + k_2}$$

Three cases can be distinguished:

Case I $k_{-1} \ll k_2$

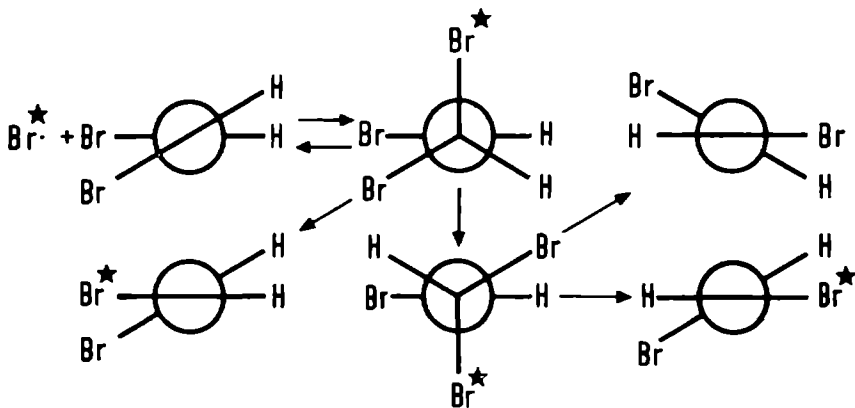
The rotation rate of the intermediate radical is very great compared with its dissociation rate. The rate of attack of halogen atoms on the double bond (k_1) is now rate-determining since each attacking halogen atom effects isomerization. k_{-1} will be small when the C-X bond is strong and this will probably be the case when chlorine atoms are used as a catalyst. The rate law then reduces to:

$$v = k_1 [\text{cis}] [\text{X}\cdot]$$

Case II $k_{-1} \approx k_2$

When k_{-1} and k_2 are of comparable size the rate law cannot be sim-

plified. It has been found by Steinmetz and Noyes⁴ that this is the case with the bromine atom catalyzed isomerization of dibromoethylene. These authors measured the exchange rate of radioactive bromine with *cis*-1,2-dibromoethylene and the rate of *cis*-*trans* isomerization under the same circumstances.



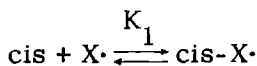
The exchange rate is about two times as rapid as the isomerization to *trans*-dibromoethylene. This means that the intermediate *cis*- $C_2H_2Br_3\cdot$ radical rotates to the isomeric *trans* radical with a rate comparable to that with which it loses a bromine atom ($k_{-1} \approx k_2$). The kinetics were complicated in this reaction by the concurrent addition of bromine to the double bond.

Case III $k_{-1} \gg k_2$

Similar measurements have been performed by Noyes, Dickinson and Schomaker⁵ with diiodoethylene and radioactive iodine. In this case the exchange rate was 10^2 - 10^3 times the isomerization rate. This is therefore an example of the third case ($k_{-1} \gg k_2$). The rate law then becomes:

$$v = \frac{k_1}{k_{-1}} k_2 [\text{cis}] [X\cdot] = K_1 k_2 [\text{cis}] [X\cdot]$$

in which K_1 is the equilibrium constant of



The high k_{-1}/k_2 ratio in the case of diiodoethylene and iodine can be explained in two different ways. Firstly the weaker C-I bond compared with the C-Br bond may lead to a greater dissociation rate for the intermediate radical (k_{-1}) in the case of iodine and secondly the rotation rate

of the $C_2H_2I_3\cdot$ radical will be slower than that of the $C_2H_2Br_3\cdot$ radical because of the greater steric requirements of the iodine atoms compared with the bromine atoms.

I.3 IODINE ATOM CATALYZED CIS-TRANS ISOMERIZATION

Iodine-catalyzed isomerization of dichloroethylene^{6,7}, diiodoethylene⁵, cis-cinnamic acid^{8,9}, its esters^{10,11}, cis-stilbene^{12,13,14}, styrylpyridines¹⁴, butene-2¹⁵ and pentadiene-1,3¹⁶ has been studied by several authors. The iodine atoms were generated from iodine molecules either photochemically ($h\nu$) by irradiation with light or thermally (T) by heating the reaction mixture to temperatures in the neighbourhood of 100°C or higher. The activation energy of the isomerization has been found to be about 19-20 kcal higher when the iodine atoms were produced thermally than when they were generated by light. This difference is equal to one half of the dissociation energy of the iodine molecule. The reaction rate has been found to be first order with respect to cis compound and half order with respect to iodine. This indicates that iodine atoms are indeed the reactive species. Under constant illumination or at constant temperature the iodine atoms are present in steady state concentration:

$$[I\cdot] = K_I^{1/2} [I_2]^{1/2}$$

in which K_I is the equilibrium constant of: $I_2 \xrightleftharpoons{K_I} 2I\cdot$

T a b l e I I
Iodine-catalyzed cis-trans isomerizations

Olefin	Activation energy (kcal/mole)		Solvent	References
	T	$h\nu$		
cis- $C_2H_2I_2$	31.3	11.0	decalin	5
cis- $C_2H_2Cl_2$	31.2	11.9	benzene	6,7
cis-cinnamic acid	24.2	4.8	benzene	8,9
cis-stilbene	25	3.6	hexane	12,13,14

T = thermally induced reaction

$h\nu$ = photochemically induced reaction

Replacement of the concentration of iodine atoms in the formulas in section I.2 by $K_1^{1/2} [I_2]^{1/2}$ shows that the reaction rate should be proportional to the square root of the iodine concentration.

In table II some data of iodine-catalyzed cis-trans isomerizations reported in the literature are given. All authors agree to the mechanism as described previously. For the isomerization of cis-stilbene¹³ with iodine and light in the wavelength region 360-430 m μ another mechanism has also been proposed in which molecular complexes of cis-stilbene and iodine play a role. Such complexes are also formed in the iodine-catalyzed isomerization of cis-azobenzene¹⁷.

Visscher and Kooyman^{10,11} have measured the rate of cis-trans isomerization of cis-cinnamic esters under the influence of thermally generated iodine atoms. The methyl, ethyl, n-propyl, i-propyl, and cyclopentyl esters reacted 2-2.5 times faster than cis-cinnamic acid, the tert.-butyl ester was more than three times as reactive as the free acid. These results would not have been anticipated if the approach of the catalytic iodine atom to the double bond was rate-determining. Thus, according to the Newman Rule of Six¹⁸, the approach of the catalytic species should be subject to increasing steric shielding as the number of atoms in the 6-position with respect to the carbon atom attacked increases. Hence the results were interpreted in terms of a rapidly reversible addition of an iodine atom, followed by a relatively slow rotation about the C $_{\alpha}$ -C $_{\beta}$ bond of the intermediate radical. This interpretation is therefore analogous to that proposed by Noyes and coworkers⁵ for the reaction between cis-1,2-diiodoethylene and radioactive iodine. The rate differences were believed to be mainly due to differences in the release of strain on formation of the primary adduct-radical. Thus it was believed that the nature of the alkyl residue in the esters would influence K_1 mainly and k_2 would be nearly constant for all cis-cinnamic esters (see rate law in section I.2).

I.4 OBJECTIVES AND SURVEY OF THE PRESENT STUDY

The investigation by Visscher and Kooyman^{10,11} on the iodine-catalyzed isomerization of cis-cinnamic esters is the first study in which the effects of structural variations of the cis compound on the rate of the reaction has been analyzed. Although the differences in the chosen series of compounds lie only in the spatial extensiveness of the ester function, kinetic data provided arguments indicating the rotation step as the rate-determining one. Other problems concerning the mechanism

remained outstanding, e.g. the nature of the intermediate. The authors used a structure with a covalent C-I bond, but did not exclude the possibility of an ion pair $\text{cis}^{\oplus}\text{I}^{\ominus}$.

We thought it worthwhile to extend these investigations to a series of compounds, in which, by the introduction of a wide variety of substituents, the influence of electronic effects (inductive or conjugative) on the rate of isomerization could also be analyzed. Furthermore the results of such a study might elucidate the structure of the transition state and thus provide information about the rate-determining step of the reaction.

Cis-stilbene was chosen as the parent compound of our series because of its symmetrical structure. The olefinic carbon atoms of this compound are equivalent, so it makes no difference which carbon atom will be attacked by iodine atoms. The iodine-catalyzed isomerization of cis-stilbene will therefore occur via only one intermediate and this will simplify a quantitative interpretation of the results. In order to keep this advantage with cis-stilbene derivatives only symmetrically substituted cis-stilbenes were studied.

Another advantage of stilbene is that the energy difference between cis and trans compound is large (5-6 kcal¹⁹), so that the equilibrium $\text{cis} \rightleftharpoons \text{trans}$ lies far to the right and trans-cis isomerization can be neglected. There is also a great difference in the U.V. absorption spectra of cis- and trans-stilbenes which will make an accurate spectrophotometric analysis of the reaction mixture possible. Finally, both in Leiden and in Nijmegen many studies have been carried out using cis- and trans-stilbene derivatives and we could make use of the experience gained with these compounds.

Thus the iodine-catalyzed isomerization of 18 symmetrically substituted cis-stilbenes has been studied at temperatures of 70^o-120^o and different iodine concentrations using carbon tetrachloride as solvent. Isomerization was induced by thermally generated iodine atoms.

Chapter II deals with the experimental methods. The results are summarized and discussed in Chapter III and IV. In Chapter V special attention is paid to the isomerization of 4,4'-dimethoxy-cis-stilbene which can also take place via a different and particularly interesting mechanism. Finally, Chapter VI deals with the syntheses of the compounds.

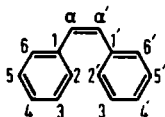
I.5 NOTATION FOR THE CIS- AND TRANS-STILBENE DERIVATES

The following notation is used to represent the symmetrically sub-

stituted cis- and trans-stilbene derivatives.

Cis-stilbenes are represented by a capital C, trans-stilbenes by a capital T. The position and character of the substituents follow using conventional symbols. 3,3'-dibromo-cis-stilbene for instance is represented as C3Br, 4,4'-dimethyl-trans-stilbene as T4CH₃ and 3,5,3',5'-tetramethyl-cis-stilbene is C3,5(CH₃)₂.

In order to avoid confusion the numbering of the stilbenes is indicated in the adjacent figure.



CHAPTER II

EXPERIMENTAL METHODS

II.1 MATERIALS USED

Isomerizations were carried out using *carbon tetrachloride* (Merck p.a.) as solvent. It was distilled in an atmosphere of nitrogen and stored in a tightly stoppered bottle.

Iodine (Merck p.a.) was used without further purification.

Tank nitrogen used was of a special quality (Loosco 'groenband' nitrogen) and contained practically no oxygen. It was further purified by passing through a column (5 x 100 cm) of BTS catalyst heated to 180°C. After 3000 l of nitrogen had flown through the column only 5 cm of the catalyst had turned grey. In order to remove water lost by the catalyst a calcium chloride drying tube was used (see fig.1).

II.2 GENERAL MEASURING PROCEDURE

The method applied by Visscher¹⁰ for the measurements of the rate constants of the iodine-catalyzed isomerizations of *cis*-cinnamic esters was also used by us with modifications.

From *cis*-stilbenes stock solutions of a concentration of 0.1 mole/l were prepared. Three stock solutions of iodine were prepared of concentrations 0.04, 0.01 and 0.002 mole/l. The reaction mixtures were made by mixing together equal volumes of the *cis*-stilbene and iodine solutions from a pipette giving concentrations of 0.05 mole/l for the *cis*-stilbenes and 0.02, 0.005 or 0.001 mole/l for iodine.

The reactions were carried out in tubes (5 x 200 mm for volumes of 2 ml and 3.5 x 100 mm for volumes of 0.2 ml) which were sealed under nitrogen and placed in a thermostat. After appropriate times the tubes were removed from the thermostat and their contents analyzed spectrophotometrically.

II.3 OTHER PROCEDURES

In the case of 4,4'-dicyanostilbene, 4,4'-dinitrostilbene and 3,3'-dinitrostilbene the trans compounds are poorly soluble in carbon tetrachloride. T3,5Br₂ dissolves slowly in this solvent. Reaction mixtures were therefore diluted with chloroform in which these stilbenes dissolved sufficiently well for spectrophotometric analysis.

C4CN is poorly soluble in carbon tetrachloride at room temperature. Reaction tubes were filled with about 2 mg of solid cis compound and 0.2 ml of iodine solutions of concentrations 0.02, 0.005 and 0.001 mole/l respectively. The tubes were shaken in the thermostat until, after half a minute, the reaction mixture became homogeneous. The same technique was applied to C4NO₂ but here the solubility was so bad that at 120°C only 10 mg of the cis compound dissolved in 1 ml of carbon tetrachloride. Measurements could therefore only be carried out at 120°C with concentrations of C4NO₂ of 0.02 mole/l.

II.4 INFLUENCE OF OXYGEN

Although in previous work on the iodine-catalyzed isomerization of cis-cinnamic acid^{8,9}, its esters^{10,11} and cis-stilbene^{12,13,14} oxygen was not reported to influence the reaction rate it does appear to exert a marked influence in our case.

In some preliminary experiments we measured rate constants of cis-trans isomerizations of cis-stilbene under various conditions with respect to the exclusion of oxygen. In table I rate constants are summarized for the isomerization of cis-stilbene with various iodine concentrations and different sealing procedures.

T a b l e I
Isomerization rate constants for cis-stilbene *

	sealed under air	sealed under impure nitrogen	sealed under purified nitrogen	
T (°C) →	100°	100°	100°	90°
[I ₂]				
0.02		2.45	2.72	1.27
0.005	1.25	2.00	2.82	1.28
0.001	1.17	1.80		1.31

* k values are derived from $-d[\text{cis}]/dt = k[\text{cis}][\text{I}_2]^{1/2}$ and are expressed in $l^{1/2} \text{mole}^{-1/2} \text{h}^{-1}$.

It can be seen from these figures that oxygen inhibits the reaction especially at iodine concentrations for which the inhibitor/catalyst ratio is high. It was therefore decided to seal the reaction tubes under purified nitrogen. We made the criterion for the absence of oxygen be that the reaction constants obtained should be independent of the iodine concentration up to a twentyfold variation of this concentration*.

II.5 SEALING TECHNIQUE

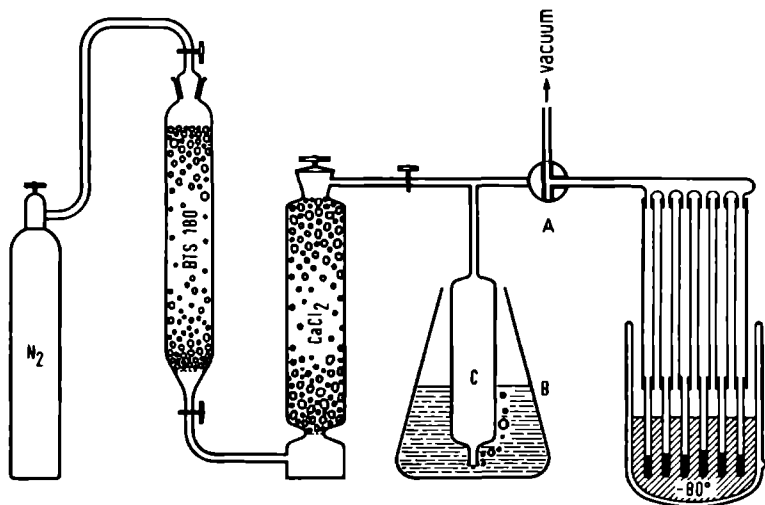


Figure 1
Sealing apparatus

Reaction tubes were connected to the apparatus drawn in fig. 1. Ten tubes could be treated simultaneously in this procedure. They were cooled in a mixture of solid carbon dioxide and acetone at -80° whereupon the contents solidified. They were evacuated to a pressure of 0.1 mm Hg, after which purified nitrogen was admitted via stopcock A. Nitrogen, which flowed at a constant rate through the apparatus and normally escaped through a flask B, partly filled with paraffin oil, streamed quickly into the reaction tubes while the buffering volume C became filled with oil. By switching stopcock A the tubes were again evacuated and filled with nitrogen. The procedure was repeated five times. The tubes were then warmed up to room temperature in order

* In a preliminary communication²⁰ some results have been published which were obtained using an insufficient technique for the exclusion of oxygen. We realize that these data must be less accurate.

to allow any little bubbles of air that might have settled in the solid reaction mixture escape. During this warming up the tubes remained connected to the nitrogen source. They were now cooled again and the vacuum/nitrogen process repeated another five times. The tubes were then sealed off while still connected to the nitrogen source.

II.6 INFLUENCE OF LIGHT

As can be expected in a reaction catalyzed by iodine atoms light may have a large influence on the reaction rate. Since the dissociation energy of iodine molecules is only 36 kcal/mole, dissociation can already be effected by red light.

In preliminary experiments we placed an ordinary 40 watt bulb at a distance of one metre from the thermostat in which the reactions were carried out. The reaction rate appeared to be about six times greater than when the reaction was carried out in total darkness.

We therefore decided to place the thermostat in a fume cupboard made impenetrable to light. Even when this fume cupboard was placed in broad daylight a photographic paper was not darkened on development after three hours in the fume cupboard. All manipulations with the reaction tubes were carried out in time intervals as short as possible. During these operations the laboratory was only sparingly illuminated and all solutions were shielded from direct radiation.

Absorption cells in which the optical densities of the resulting solutions were measured were transported in a special case from which they could be placed directly in the spectrophotometer without being exposed to light.

II.7 SPECTROPHOTOMETRIC ANALYSIS

In Visscher's original procedure¹⁰ the contents of a reaction tube consisted of 1 ml of cis compound solution and 1 ml of iodine solution. After the reaction these contents were transferred quantitatively to a standard flask and diluted to 50 ml with carbon tetrachloride. This solution was again diluted 50 times. From the resulting solution the optical density was measured at an appropriate wavelength at which extinction coefficients for cis and trans compounds differed sufficiently. For cis-cinnamic acid and -esters the extinction coefficients at 272 m μ are about half the extinction coefficients for the corresponding trans

compounds.

Rate constants k can then be calculated from:

$$k = \frac{1}{t} \ln \frac{D_{\infty} - D_0}{D_{\infty} - D_t} [I_2]^{-1/2} I_1^{1/2} \text{mole}^{-1/2} \text{h}^{-1} \quad (1)$$

in which D_0 , D_t and D_{∞} are optical densities of the solutions at reaction times $t = 0$, $t = t$ and $t = \infty$.

Since at about $310 \text{ m}\mu$ extinction coefficients for cis- and trans-stilbenes differ by a factor 5 the spectrophotometric analysis is even more applicable in this case. As an example the change of spectrum of cis-stilbene during the reaction is shown in fig. 2. In fig. 3 values of $\ln \left[\frac{D_{\infty} - D_0}{D_{\infty} - D_t} \right]$ are plotted against t . A correct first order plot is obtained.

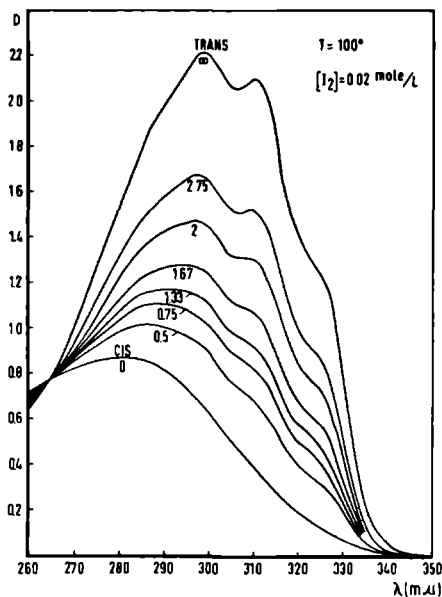


Figure 2
Change of spectrum
during the isomerization of
cis-stilbene to trans-stilbene

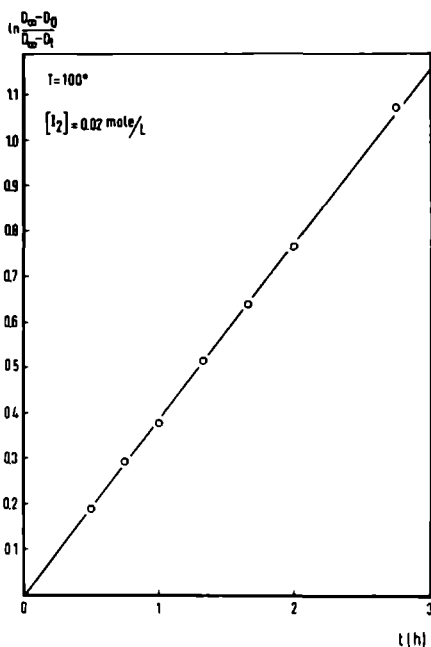


Figure 3
First order plot
for isomerization
of cis-stilbene

As can be seen from fig. 2 a point is found at wavelength $265 \text{ m}\mu$ at which cis- and trans-stilbene have equal extinction coefficients. The occurrence of this isosbestic point which has been found for almost all

pairs of cis- and trans-stilbenes at about 265 m μ offered possibilities of simplifying the measuring procedure and reducing the amount of material needed for a reaction rate measurement. Moreover the isosbestic point furnished a good test for the absence of side reactions in which stilbene might be consumed.

In the procedure described above for each reaction rate measurement as many millilitres of cis compound solution are used as reaction tubes are taken whereas 1 ml of cis-stilbene solution mixed with 1 ml of iodine is now sufficient. The resulting mixture is divided over a number of small reaction tubes (3.5 x 100 mm) in arbitrary portions by means of a Pasteur capillary pipette. After the reaction the contents of the tubes are diluted roughly to the proper concentration for spectrophotometric analysis, the ratios of the optical densities at $\lambda = 310$ m μ and the isosbestic point (R_0 , R_t and R_∞) are measured and these values used instead of D_0 , D_t and D_∞ respectively.

II.8 ACCURACY OF THE MEASUREMENTS

Since five quantities must be measured for any rate measurement there are five possible sources of errors. Their influence will be analyzed now.

The *temperature* of the oil in the thermostat was regulated by means of a contact-thermometer. Temperatures fluctuated regularly about the measuring temperatures (70 $^\circ$; 80 $^\circ$; 90 $^\circ$; 100 $^\circ$; 120 $^\circ$ C) with an amplitude of $\pm 0.1^\circ$ C. Since a variation of 0.1 $^\circ$ C causes a 1% change in reaction rate this error is negligible. A systematic error may be caused by the uncertainty in the absolute value of the temperature ($\pm 0.5^\circ$ C).

Since shortest *times* measured are about 15 min and warming up of the small tubes occurs within half a minute this error is negligible.

Optical densities at time $t = 0$ and $t = \infty$ (D_0 ; D_∞ resp. R_0 and R_∞) were determined from the spectrum of cis- and trans-stilbenes. An infinity reading was also made from the reaction mixture. The infinity reading was always in very good agreement with the value determined from the spectrum of the trans-stilbene derivate, except in the few cases where impure samples were used. This indicates that no trans-cis isomerization occurs and we have only to deal with cis-trans isomerization. Values of R_0 and R_∞ for one stilbene derivative once determined were used in all measurements of the respective compound. Slight errors in these two quantities will cause therefore only a small and constant systematic error.

Errors in the determination of optical densities at time t (R_t or D_t) are therefore the most important ones in the estimation of k values.

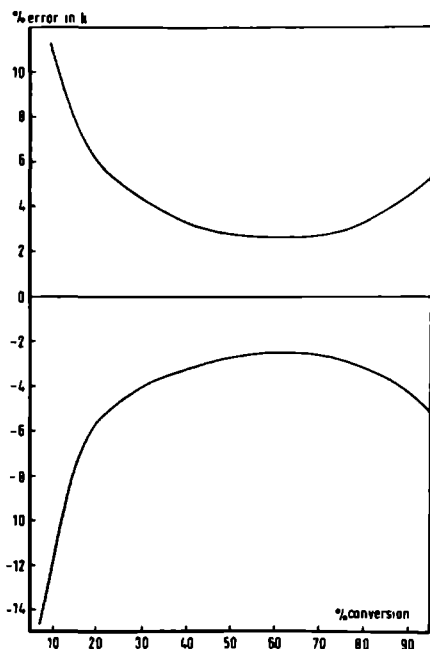


Figure 4
Dependence of the accuracy of k
on the conversion percentage,
assuming constant absolute error in D_t

If it is assumed that the absolute error in D_t is independent of the conversion percentage and amounts roughly to ± 0.02 while D_t varies from 0.3 (D_0) to 2.3 (D_∞) the accuracy of the obtained k values depends on the conversion percentage as indicated in fig. 4. As can be seen from this figure the error in k remains nearly constant ($\pm 3\%$) in a very broad range (30-85% conversion). This means that in the plot of $\ln[(D_\infty - D_0)/(D_\infty - D_t)]$ against t the error in the former expression is proportional to t in the indicated region. Hence the conditions for using the method of least squares in compiling the best line through the measured points is not fulfilled*. Another procedure had to be applied for the statistical treatment of the results (see II.9).

In fact the accuracy of D_t becomes somewhat greater at low and smaller at high conversions but this makes the reasoning even more accurate. It will also cause a shift of the region in which k is of constant accuracy to lower conversion percentage.

* Guggenheim and Prue²¹ also warn against the gratuitous application of the method of least squares on any derived function of a measured quantity instead of this quantity itself.

II.9 STATISTICAL TREATMENT OF THE RESULTS

In accordance with the consideration in the preceding section it was found that within the range 20-70% conversion the accuracy of the obtained k values is independent of the conversion percentage. Thus all k values determined in this range have the same accuracy. The best method of statistical treatment is therefore to take the mean value of a series of measured k_i values and compile standard deviation and 95% confidence limits using the equations:

$$s = \sqrt{\frac{\sum (k - k_i)^2}{n - 1}}$$

in which k_i = individual k value

k = mean value of k_i

n = number of measurements (k_i values)

and $k_{\min}^{\max} (95\%) = k \pm t \frac{s}{\sqrt{n}}$

in which t = Student's t .

For the example given in section II.7 (fig. 3) the following data were obtained:

time (hours)	$\ln \frac{D_{\infty} - D_0}{D_{\infty} - D_t}$	k_i
0.50	0,189	2.674
0.75	0,292	2.752
1.00	0,378	2.676
1.33	0,515	2.736
1.67	0,639	2.706
2.00	0,765	2.705
2.75	1,071	2.757

$$k_{\min} = 2.68 \quad k = 2.72 \quad k_{\max} = 2.75 \quad s = 0.035$$

At each temperature and iodine concentration a series of 3-10 measurements was made. Owing to the large amount of calculations, these were carried out by a computer.*

* Calculations and computer programming were performed by Drs. W.H. Doesburg.

II.10 U.V. SPECTRA

In table II data from the U.V. absorption spectra of the pure compounds investigated are reported. The spectra were recorded on a Beckman DK-2A spectrophotometer using solutions in carbon tetrachloride unless otherwise stated.

T a b l e II
U.V. absorption data
of symmetrically substituted cis- and trans-stilbenes

Ring-substituents	$\lambda_{\text{cis max}}$	$\epsilon_{\text{cis max}}$	$\lambda_{\text{trans max}}$	$\epsilon_{\text{trans max}}$	λ_i	λ_m
none	282	10650	299	26900	265	311
3CH ₃	284	10300	311	25750	265.5	313
			303	27700		
3OCH ₃	290	10050	314	27200	-	318
			307	23800		
3Cl	278	9750	318	22850	265	310
			300	28000		
3Br	281	9880	301	27700	266.5	310
3I	1)	1)	304	28400	267	310
3NO ₂ 2)	265	27900	~280	34500 3)	265	305
3tBu	278	9950	303	27200	266	313
			314	26500		
3,5Br ₂ 2)	283	9960	301	32700 3)	268	310
			328	18800 3)		
3,5(CH ₃) ₂	289	10600	307	27600	269.5	315
			316	27600		
4CH ₃	288	12000	305	28700	265.5	318
			318.5	28300		
4OCH ₃	295	15900	311	30100	275.5	328
			328	27800		
4Cl	289	13400	306	33350	271.5	319
			319.5	33700		
4CN 2)	298	16150	317	39900	289	328
			328	45000		
4NO ₂ 2)	328	16400	344.5	26600	318	360
			358	40700 3)		
2CH ₃	268	10700	297	20200	260	305
2Cl	271	10400	296	22300	268.5	305
2I	no maximum		298	20300	271.5	310
4-monomethoxy- stilbene	291.5	13400	309	27800	272	321
			322	27000		

λ_{\max} = wavelength of the absorption maxima (m μ)

ϵ_{\max} = extinction coefficient at the absorption maxima (in l mole⁻¹ cm⁻¹)

λ_i = isosbestic point

λ_m = wavelength at which the reaction mixtures were analyzed

λ values are ± 1 m μ accurate

ϵ values are $\pm 3\%$ accurate

- 1) No analytically pure material was obtained.
- 2) In chloroform solution.
- 3) Infinity reading from the reaction mixture.

CHAPTER III

RESULTS

III.1 REACTION RATE CONSTANTS

The reaction rate constants calculated from the observations are listed in table I. The headings are:

T = temperature (degrees centigrade).

$[I_2]$ = iodine concentration of the reaction mixture in mole/litre.

n = number of measurements made at the same temperature and iodine concentration.

k = mean value of the n observed k_i values expressed in $\text{litre}^{1/2}\text{-mole}^{-1/2}\text{hour}^{-1}$.

s = standard deviation.

k_{\min} = lower 95% confidence limit calculated from s and n.

k_{\max} = upper 95% confidence limit calculated from s and n.

Rate constants at the same temperature but different iodine concentrations do not differ significantly from each other. This means that the reaction rate is proportional to the square root of the iodine concentration i.e. proportional to the concentration of iodine atoms. The only important exception, C_4OCH_3 at 70°C , will be discussed in the chapter devoted to this compound.

The accuracy of the measurements varies from 1-10% but most k values are 2-4% accurate. Confidence limits below + 1% might have occurred by chance. This is in good agreement with the assumptions presented in section II.8. In most cases the accuracy of the k values obtained at low iodine concentrations tends to be somewhat less than at high concentrations.

Table I
Isomerization rate constants

T	$[I_2] \times 10^3$	n	k_{\min}	k	k_{\max}	s
1 C4OCH3 (4,4'-dimethoxy-cis-stilbene)						
100	5	8	5.33	5.49	5.65	0.19
100	1	7	5.39	5.69	5.99	0.32
90	5	8	2.50	2.55	2.60	0.062
90	1	8	2.48	2.54	2.60	0.069
70	5	9	0.62	0.65	0.68	0.038
70	1	9	0.41	0.43	0.46	0.031
2 C4CH3 (4,4'-dimethyl-cis-stilbene)						
100	5	9	4.51	4.59	4.67	0.11
100	1	9	4.24	4.36	4.48	0.16
90	20	6	1.99	2.01	2.03	0.022
90	5	5	1.97	2.01	2.06	0.038
90	1	4	1.88	1.97	2.06	0.055
70	20	9	0.345	0.354	0.363	0.012
3 C3,5(CH3)2 (3,5,3',5'-tetramethyl-cis-stilbene)						
120	1	9	13.3	13.6	13.9	0.39
100	20	10	2.95	3.00	3.04	0.060
100	5	9	2.92	3.00	3.07	0.093
90	20	9	1.32	1.35	1.38	0.035
90	5	9	1.32	1.35	1.38	0.038
90	1	10	1.35	1.38	1.42	0.048
70	20	10	0.243	0.252	0.260	0.012
4 C3tBu (3,3'-di-tert.-butyl-cis-stilbene)						
120	1	8	9.25	9.47	9.69	0.26
100	20	7	2.03	2.05	2.08	0.027
100	5	7	2.08	2.14	2.20	0.065
90	20	7	0.930	0.947	0.964	0.019
90	5	5	0.931	0.943	0.955	0.010
90	1	5	0.86	0.99	1.12	0.10
70	20	9	0.170	0.175	0.179	0.0061

T	[I ₂] $\times 10^3$	n	k _{min}	k	k _{max}	s
5 C₃CH₃ (3,3'-dimethyl-cis-stilbene)						
120	1	8	12.7	13.1	13.5	0.44
100	20	7	2.92	2.96	3.00	0.043
100	5	8	2.88	2.96	3.03	0.091
90	20	4	1.31	1.32	1.33	0.0039
90	5	4	1.30	1.33	1.36	0.018
90	1	4	1.30	1.33	1.36	0.021
70	20	9	0.240	0.243	0.245	0.0034
6 CH (cis-stilbene)						
120	1	9	12.4	12.6	12.9	0.36
100	20	7	2.68	2.72	2.75	0.035
100	5	6	2.78	2.82	2.86	0.039
90	20	5	1.25	1.27	1.29	0.015
90	5	4	1.20	1.28	1.36	0.049
90	1	6	1.25	1.31	1.37	0.056
70	20	7	0.213	0.217	0.222	0.0049
7 C₃OCH₃ (3,3'-dimethoxy-cis-stilbene)						
120	1	9	9.03	9.19	9.34	0.20
100	20	8	1.94	2.01	2.07	0.082
100	5	8	2.00	2.03	2.06	0.039
90	20	7	0.91	0.92	0.94	0.021
90	5	8	0.89	0.91	0.93	0.025
90	1	4	0.91	0.94	0.96	0.015
70	20	9	0.151	0.153	0.155	0.0021
8 C₄Cl (4,4'-dichloro-cis-stilbene)						
120	1	8	8.79	9.10	9.41	0.37
100	20	9	1.72	1.74	1.76	0.028
100	5	8	1.79	1.82	1.86	0.043
90	20	10	0.734	0.744	0.754	0.014
90	5	10	0.745	0.760	0.776	0.022
90	1	9	0.741	0.769	0.796	0.035
70	20	8	0.128	0.133	0.138	0.0062
9 C₃I (3,3'-diiodo-cis-stilbene)						
120	5	6	4.17	4.24	4.31	0.064
100	20	5	0.88	0.91	0.94	0.026
100	1	5	0.91	0.93	0.96	0.018
90	20	5	0.371	0.385	0.399	0.011
90	5	5	0.374	0.390	0.407	0.013
70	20	9	0.0647	0.0655	0.0662	0.0010

T	$[I_2] \times 10^3$	n	k_{\min}	k	k_{\max}	s
10 C3Cl (3,3'-dichloro-cis-stilbene)						
120	5	10	3.99	4.05	4.12	0,092
100	20	10	0.831	0.849	0.867	0,025
100	5	10	0.842	0.852	0.862	0,014
90	20	10	0.373	0.377	0.380	0,0050
90	5	9	0.361	0.370	0.379	0,012
90	1	9	0.365	0.383	0.401	0,023
70	20	10	0.0547	0.0561	0.0575	0,0019
11 C3Br (3,3'-dibromo-cis-stilbene)						
120	5	8	4.18	4.23	4.29	0,065
100	20	9	0.835	0.848	0.861	0,016
100	5	10	0.847	0.860	0.872	0,018
90	20	10	0.367	0.373	0.379	0,0083
90	5	10	0.362	0.368	0.374	0,0082
90	1	10	0.366	0.380	0.394	0,019
70	20	10	0.0587	0.0597	0.0607	0,0014
12 C4CN (4,4'-dicyano-cis-stilbene)						
120	5	9	5.80	5.92	6.04	0.16
100	20	9	1.21	1.25	1.29	0,057
100	5	7	1.19	1.24	1.29	0,056
90	5	9	0.567	0.578	0.589	0,014
90	1	8	0.588	0.622	0.656	0,040
13 C3NO₂ (3,3'-dinitro-cis-stilbene)						
120	20	9	1.66	1.70	1.75	0,054
120	5	5	1.83	1.86	1.89	0,022
120	1	3	1.32	1.52	1.72	0,081
100	20	10	0.318	0.331	0.345	0,019
100	5	10	0.318	0.337	0.355	0,025
90	20	5	0.137	0.147	0.156	0,0075
14 C3,5Br₂ (3,5,3',5'-tetrabromo-cis-stilbene)						
120	20	8	1.53	1.57	1.60	0,045
120	5	5	1.49	1.60	1.71	0,089
120	1	5	1.60	1.74	1.89	0,12
100	20	6	0.320	0.334	0.348	0,014
100	5	8	0.336	0.353	0.369	0,020
90	20	7	0.134	0.137	0.140	0,0033
80	20	8	0.0543	0.0551	0.0559	0,00097

T	$[I_2] \times 10^3$	n	k_{\min}	k	k_{\max}	s
15 C ₂ CH ₃ (2,2'-dimethyl-cis-stilbene)						
120	5	9	4.29	4.33	4.37	0.053
100	20	7	0.99	1.01	1.03	0.018
100	5	7	0.99	1.01	1.03	0.023
90	20	8	0.406	0.415	0.424	0.011
90	5	8	0.416	0.421	0.426	0.0061
90	1	6	0.418	0.441	0.465	0.022
70	20	9	0.0661	0.0671	0.0681	0.0013
16 C ₂ Cl (2,2'-dichloro-cis-stilbene)						
120	20	9	2.18	2.20	2.21	0.021
120	1	5	2.07	2.28	2.48	0.16
100	20	10	0.448	0.453	0.459	0.0078
100	5	9	0.454	0.463	0.472	0.011
90	20	8	0.194	0.197	0.199	0.0029
90	5	6	0.184	0.189	0.194	0.0047
70	20	10	0.0280	0.0285	0.0290	0.00070
17 C ₂ I (2,2'-diiodo-cis-stilbene)						
120	20	8	1.29	1.30	1.31	0.013
120	5	8	1.29	1.31	1.32	0.019
100	20	8	0.257	0.260	0.264	0.0040
90	20	9	0.106	0.107	0.108	0.0017
80	20	9	0.0418	0.0422	0.0426	0.00048
18 C ₄ NO ₂ (4,4'-dinitro-cis-stilbene)						
120	5	5	3.49	3.88	4.27	0.32
120	1	7	3.69	3.87	4.06	0.20

LEGENDS TO FIGURES 1a, 1b, 1c and 1d

○ = $[I_2] = 0.02$ mole/l

□ = $[I_2] = 0.005$ mole/l

△ = $[I_2] = 0.001$ mole/l

● = Values obtained on extrapolation from fig.4

The ρ values have been determined by drawing a straight line through the measured points of the compounds 1, 2, 5, 6, 7, 9, 10, 11, 13 and 14 using the method of least squares. Omission of data from the other compounds will be discussed in chapter IV.

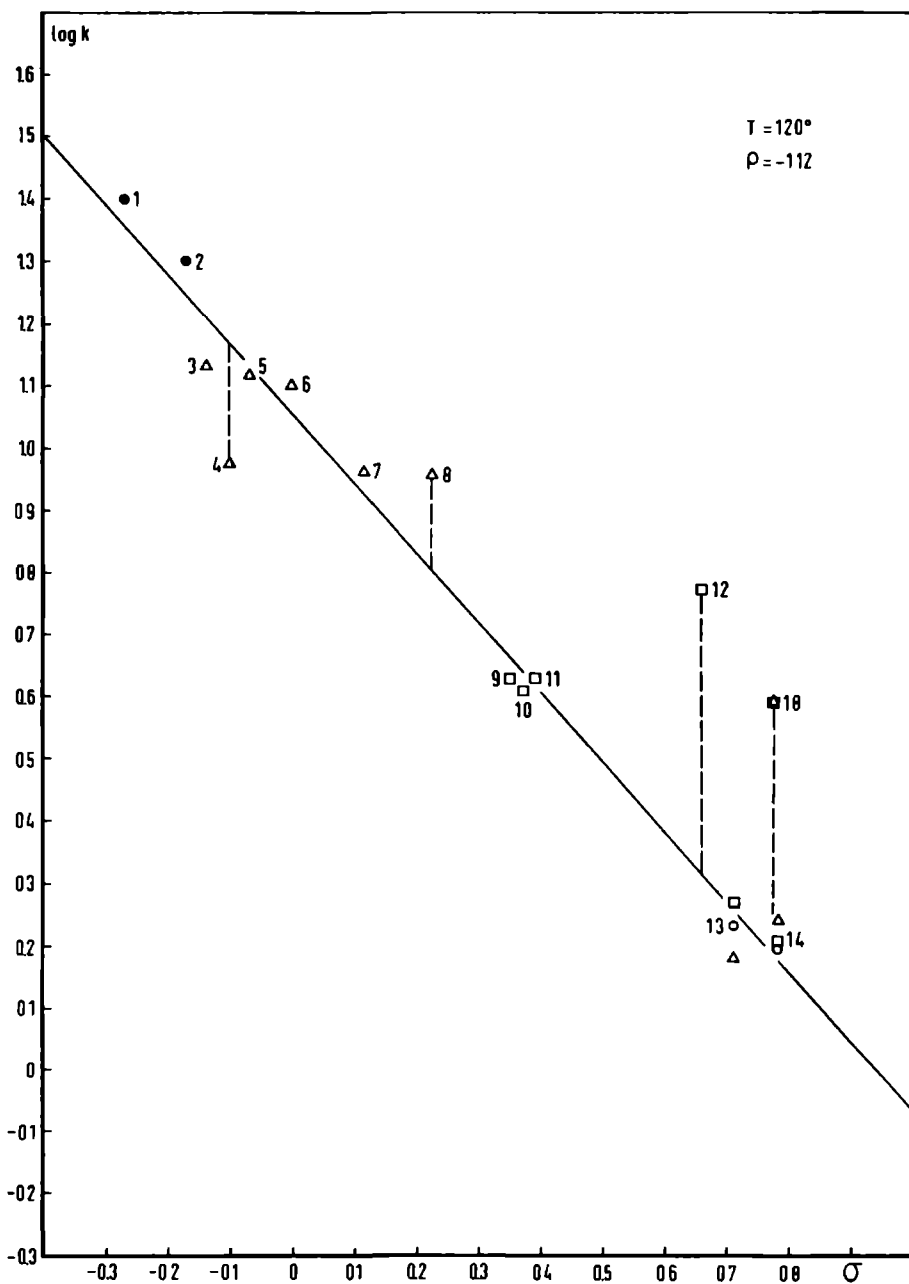


Figure 1a

Plot of $\log k$, for isomerizations of symmetrically substituted *cis*-stilbenes at 120°C , against the σ values of the substituents

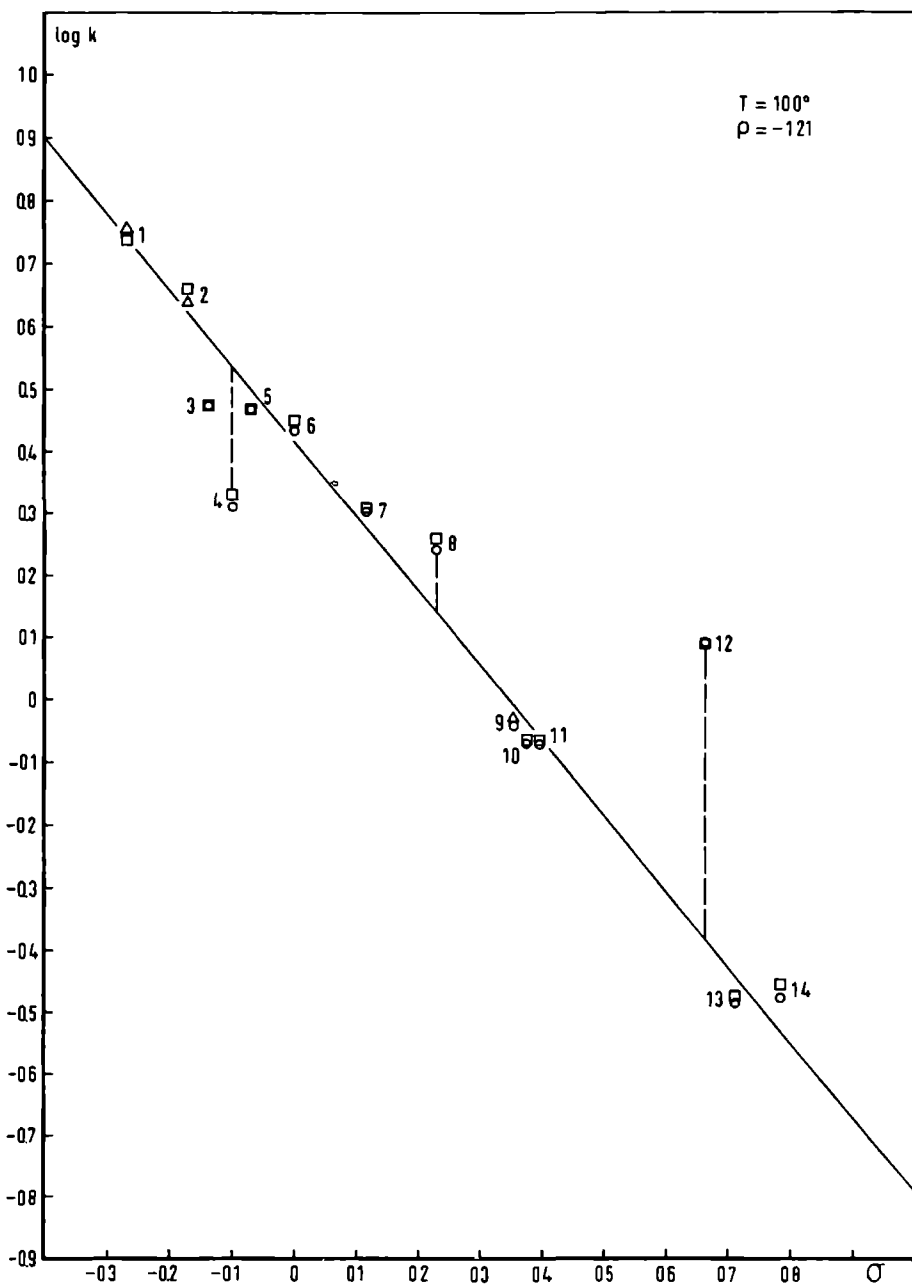


Figure 1b
Hammett plot for isomerizations of symmetrically substituted *cis*-stilbenes at 100°C

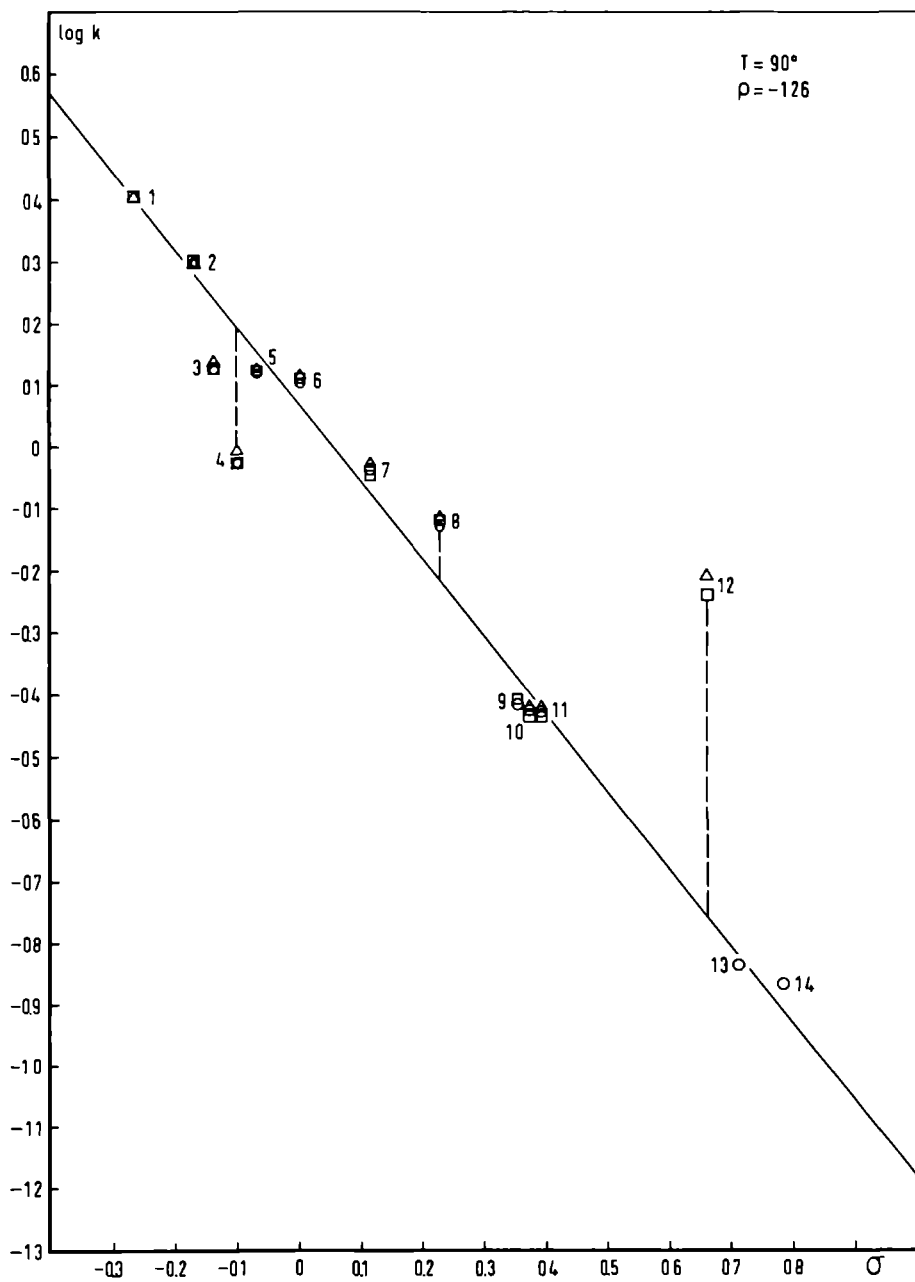


Figure 1c
 Hammett plot for isomerizations of symmetrically substituted cis-stilbenes at 90°C

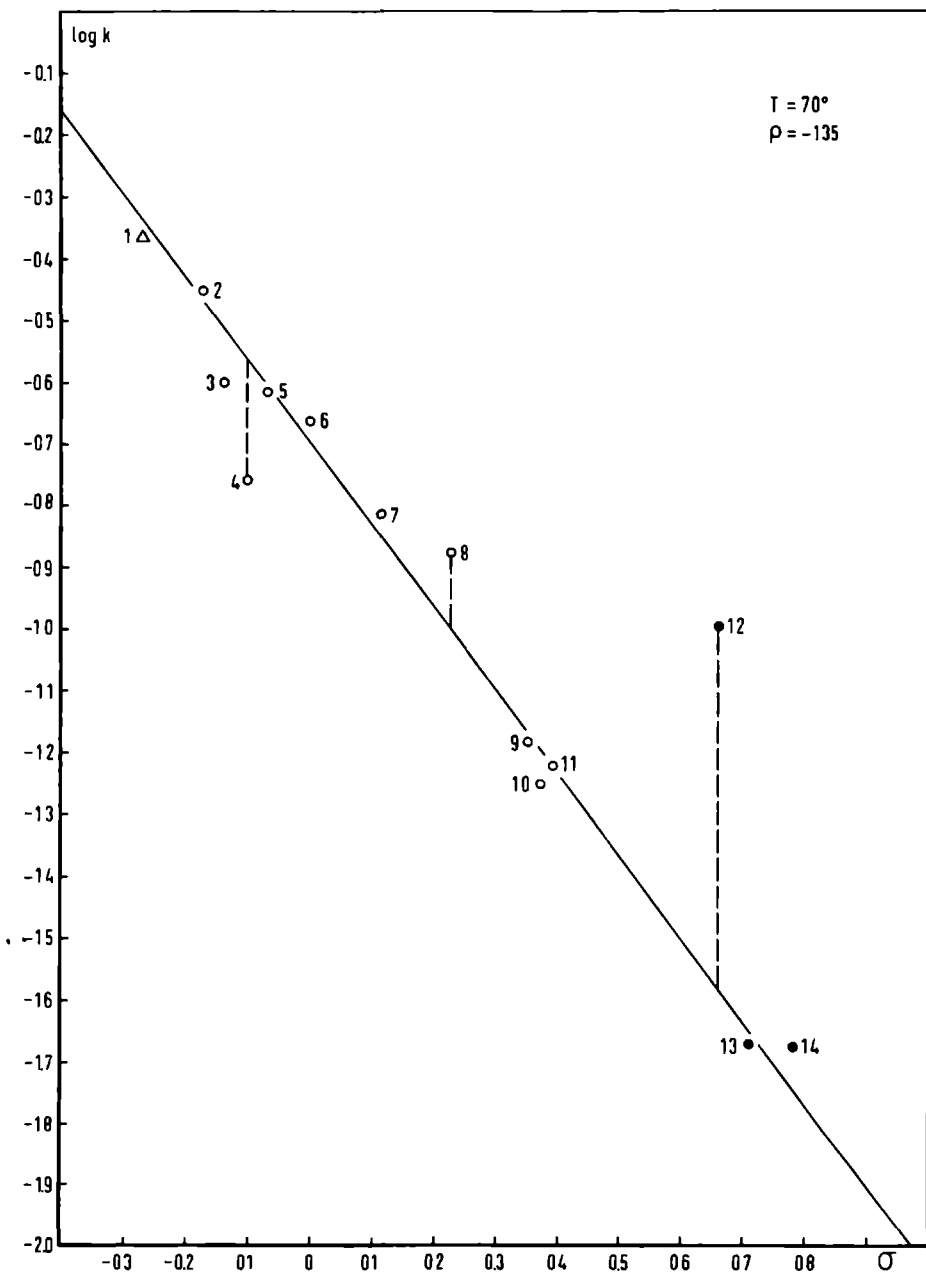


Figure 1d
 Hammett plot for isomerizations of symmetrically substituted *cis*-stilbenes
 at 70°C

III.2 HAMMETT PLOTS

As can be seen from the tables in the previous section electron-donating substituents accelerate the reaction rate whereas electron-attracting substituents retard it.

In figs. 1a,b,c,d log k values obtained at four different temperatures have been plotted against the σ values of the substituents*. With few exceptions a good linear relationship between log k and σ is found (see also table II). The ρ value depends on temperature and varies from -1.12 to -1.35. The negative sign of ρ shows that the reaction is electron-demanding with respect to stilbene. Apparently in the transition state some negative charge has been withdrawn from the stilbene molecule. This could be explained by the formation of a covalent C-I bond with a somewhat polar character and this observation is in line with the postulated intermediate for iodine-catalyzed cis-trans isomerization⁸ (fig. 2a).

Some para-substituted cis-stilbenes show positive deviations from the linear relationship. This might be due to delocalization of the odd electron into the para substituent. The transition state must then be very similar to the intermediate in fig. 2. In the formation of the C-I bond the odd electron has been transferred from the iodine atom to the stilbene moiety. The normal resonance stabilization of the organic free radical (fig. 2a-d) is strengthened by the addition of an extra resonance stabilization due to the presence of a suitable para substituent (fig. 2e). Consequently the transition state has a lower energy which leads to a higher reaction rate than would be expected from the inductive effect of the substituent alone.

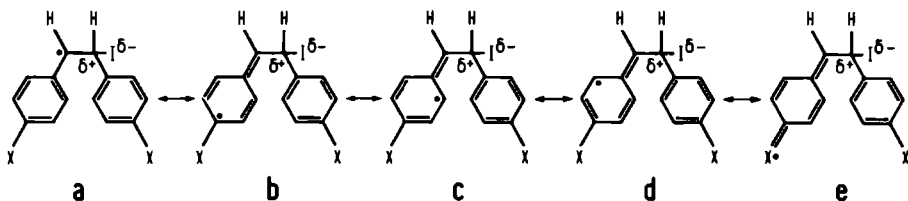


Figure 2

Illustration of the resonance stabilization of the intermediate
The transition state of the over-all reaction must be very similar to this structure.

* The σ values used are those based on the dissociation constants of benzoic acids listed in ref.22.

III.3 THE DEPENDENCE OF ρ ON TEMPERATURE

Hammett ρ values are determined from:

$$\Delta \log k_X = \rho \sigma \quad (1)$$

in which $\Delta \log k_X = \log k_X - \log k_H$

The expression for $\log k$ is:

$$\log k = \log A - E_a / 2.303 R T \quad (2)$$

Effects of substituents on the reaction rate may be caused by influences on E_a (the activation energy) or A (the frequency factor). Hence:

$$\Delta \log k_X = \Delta \log A - \Delta E_a / 2.303 R T \quad (3)$$

Combining (1) and (3) gives: $\rho \sigma = \Delta \log A - \Delta E_a / 2.303 R T$

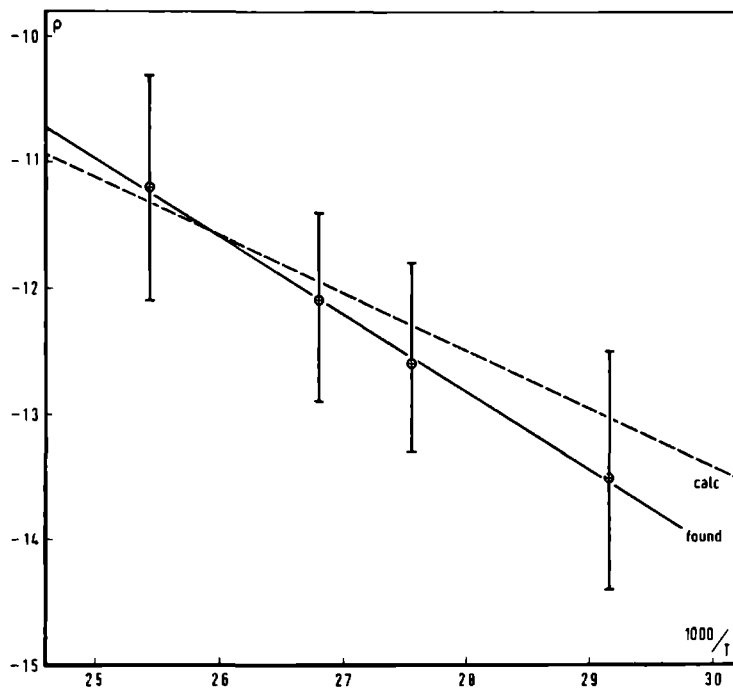


Figure 3

The dependence of ρ on temperature

(-----) = Calculated line, assuming that ρ is proportional to $-1/T$ (°K)

T a b l e II
 ρ values calculated from the Hammett lines in figs. 1a,b,c and d

T(°C)	ρ min	ρ	ρ max	r
120	- 1.03	- 1.12	- 1.21	- 0.995
100	- 1.14	- 1.21	- 1.29	- 0.997
90	- 1.18	- 1.26	- 1.33	- 0.998
70	- 1.25	- 1.35	- 1.44	- 0.996

r = Correlation coefficient between σ and $\log k$.

ρ_{\min}^{\max} = 95% confidence limits of ρ .

If $\Delta \log A$ was zero the ρ value would be proportional to $-1/T$. Indeed the observed ρ values listed in table II obey this relationship within the experimental error (dotted line in fig. 3). The relationship seems to be better described, however, by a line with a somewhat steeper slope. From this line which is represented in fig. 3 as a solid line ρ values at other than the measuring temperatures can be obtained on extrapolation.

Jaffe²³ has given a survey of the dependence of ρ on temperature for many reactions and equilibria. In most cases the proportionality of ρ vs. $-1/T$ holds, although there are reactions which show a greater slope and even reactions in which ρ strongly increases with increasing temperature. These deviations must be caused by influences of the substituent on the frequency factor of the reaction. If exact proportionality between ρ and $-1/T$ is found this influence must be zero.

III.4 ARRHENIUS ACTIVATION PARAMETERS

In fig. 4 $\log k$ values are plotted against the reciprocal of the absolute temperature for a number of cis-stilbene derivatives. From these plots Arrhenius activation parameters ($\log A$ and E_a) have been calculated together with their 95% confidence limits. For these calculations all individual measurements of $\log k_i$ have been used. Thus the number of measured points is equal to the sum of n values for a certain cis-stilbene derivative tabulated in table I. Computer calculated values are collected in table III. Regression lines of $\log k$ vs. $-1/T$ have been calculated using the method of least squares.

In accordance with the results of the previous section it appears that

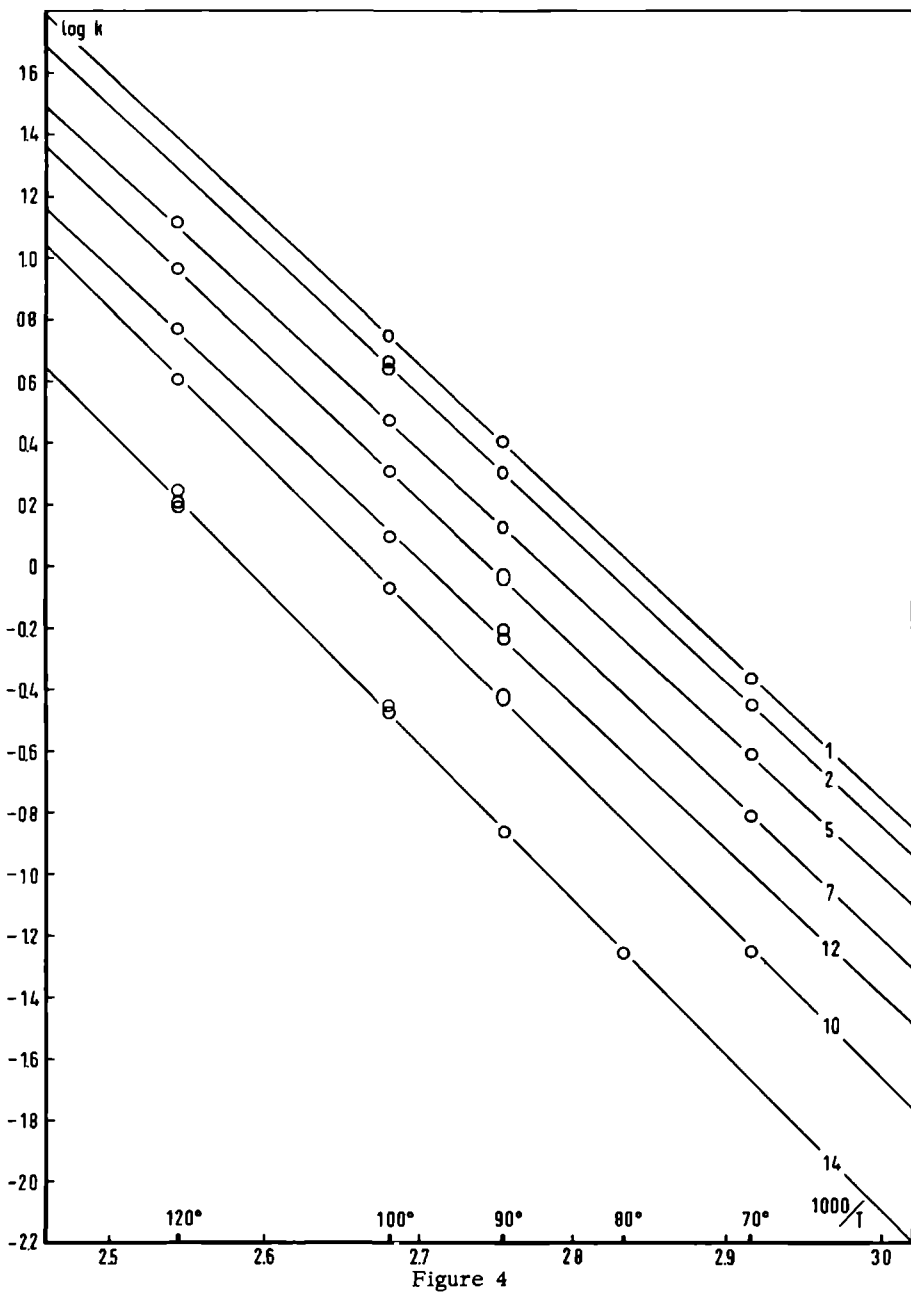


Figure 4
 Arrhenius plots of $\log k$, for iodine-catalyzed isomerizations
 of a number of cis-stilbene derivatives,
 against the reciprocal of the absolute temperature

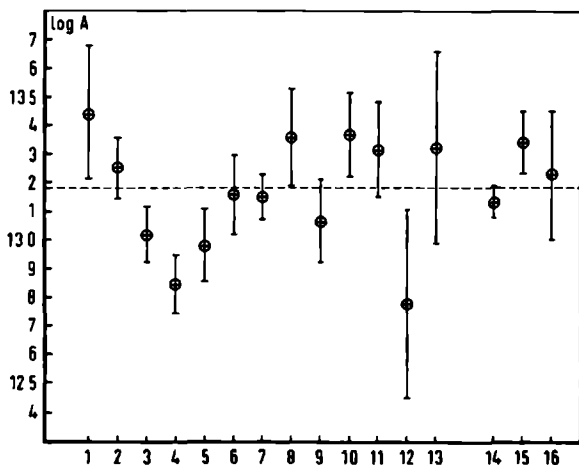


Figure 5
Schematic representation of frequency factors
Horizontal scale: compound numbers

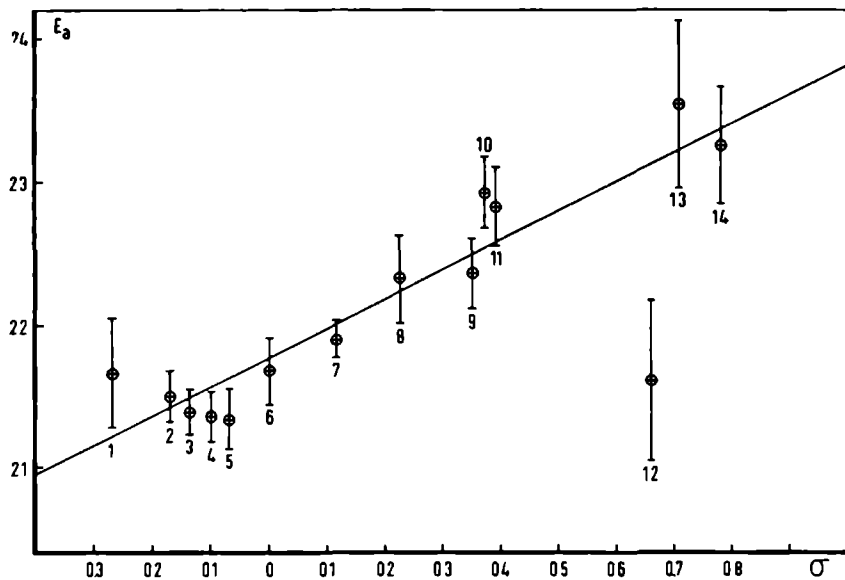


Figure 6
The observed activation energies for iodine-catalyzed isomerizations of symmetrically substituted cis-stilbenes as a function of the σ values of the substituents

Table III
Arrhenius activation parameters

Cis-stilbene	Σn	$\log A_{\min}$	$\log A$	$\log A_{\max}$	E_a^{\min}	E_a	E_a^{\max}	r
C4OCH ₃	40	13.21	13.44	13.68	21.28	21.66	22.05	0.999
C4CH ₃	42	13.14	13.25	13.35	21.32	21.50	21.68	1.000
C3,5(CH ₃) ₂	66	12.92	13.02	13.11	21.23	21.39	21.55	1.000
C3tBu	48	12.74	12.84	12.95	21.18	21.36	21.53	1.000
C3CH ₃	44	12.85	12.98	13.10	21.13	21.34	21.55	1.000
CH	44	13.01	13.15	13.29	21.44	21.68	21.91	1.000
C3OCH ₃	53	13.07	13.15	13.22	21.77	21.90	22.03	1.000
C4Cl	62	13.18	13.35	13.52	22.05	22.33	22.62	0.999
C3I	35	12.91	13.06	13.21	22.11	22.36	22.60	1.000
C3Cl	68	13.22	13.37	13.51	22.67	22.92	23.17	1.000
C3Br	67	13.15	13.31	13.48	22.55	22.82	23.10	1.000
C4CN	42	12.45	12.78	13.11	21.04	21.61	22.17	0.997
C3NO ₂	42	12.98	13.32	13.66	22.95	23.54	24.12	0.997
C3,5Br ₂	47	12.90	13.14	13.38	22.84	23.25	23.66	0.998
C2CH ₃	54	13.08	13.13	13.18	22.34	22.43	22.52	1.000
C2Cl	57	13.23	13.34	13.45	23.18	23.36	23.54	1.000
C2I	42	13.00	13.23	13.45	23.19	23.58	23.96	0.999

The headings in Table III are:

- Σn = number of measured points on which the calculations are based
 $\log A$ = logarithm of the frequency factor in $l^{1/2}\text{mole}^{-1/2}\text{h}^{-1}$, calculated by extrapolation of the regression line to $-1/T = 0$.
 $\log A_{\min}$ = lower 95% confidence limit of $\log A$
 $\log A_{\max}$ = upper 95% confidence limit of $\log A$
 E_a = best value of the activation energy in kcal/mole, calculated from the slope of the straight line through the measured points using the method of least squares
 E_a^{\min} = lower 95% confidence limit of E_a
 E_a^{\max} = upper 95% confidence limit of E_a
 r = correlation coefficient between $\log k$ and $-1/T$

for all cis-stilbene derivatives investigated, $\log A$ values are about the same. A few deviations from the mean value (13.18) have only small significance. The only serious deviation is found for C3tBu which will be discussed in chapter IV. In the determination of the mean value of $\log A$ the value found for this compound has not been used. For convenience $\log A$ factors have also been collected graphically in fig. 5, from which the same conclusions can be drawn visually.

Clearly influences of substituents on reaction rates must be ascribed only to a variation of the relevant activation energies E_a . Consequently a graph of E_a against σ yields a linear relationship for meta- and para-substituted stilbenes (fig. 6). C4CN which deviates from the Hammett line in fig. 1 also deviates significantly in fig. 6.

III.5 DERIVATION OF A GENERAL RATE EQUATION FOR META- AND PARA-SUBSTITUTED CIS-STILBENES

Assuming that all symmetrically meta- and para-substituted cis-stilbenes (except C3tBu) show exactly the same log A factor for iodine-catalyzed isomerization (i.e. differences found are due to errors in measurement) it is possible to form a general equation for the isomerization rate of these stilbenes. Taking the average value of log A (13.18) activation energies were recalculated from: $E_a^{\text{calc.}} = (2.303 \times R \times 373) (13.18 - \log k_{100^\circ})$. The values obtained were plotted against σ and a line was drawn through these calculated points, which is shown in fig. 6. The line is described by the equation:

$$E_a = 21.78 + 2.04 \sigma \text{ kcal/mole.}$$

In the case of para-substituted stilbenes a correction (ΔE_x^i) must be introduced. This correction is proportional to the degree to which the relevant substituent X can stabilize the transition state by resonance. Its numerical value may be estimated from data obtained from homolytic phenylations of the corresponding benzene derivatives as is discussed more fully in the following chapter.

The general isomerization rate equation for meta- and para-substituted stilbenes then becomes:

$$\log k = 13.18 - \frac{21.78 + 2.04 \sigma - \Delta E_x^i}{2.303 R T}$$

This expression holds only for cis-stilbene derivatives where the inductive and mesomeric effects alone are of importance. Deviations from the expression must be interpreted as due to some other effect of the substituent such as a steric effect.

III.6 ORTHO-SUBSTITUTED STILBENES

From table I it is seen that all ortho substituents investigated slow the reaction rate irrespective of their inductive effect. Apparently these

substituents hinder the isomerization reaction for steric reasons. The inductive effect remains of importance, however, as can be seen from the difference in reaction rate of C2CH₃ and C2Cl. Although the chlorine atom has a somewhat smaller van der Waals radius than the methyl group, the electron-donating methyl group causes a threefold diminution in the reaction rate at 100° whereas the chlorine atom, with opposite inductive effect, slows down the reaction rate six times. The iodine atom which has a greater size than the chlorine atom but comparable inductive effect, causes an elevenfold diminution in the reaction rate at 100°.

Taft^{24a,25} has proposed considering $\log(k_o/k_p)$ - the log ratio of the reaction rates of an ortho- and para-substituted benzene derivative - as a measure of the steric effect of the ortho substituent on the reaction rate. In table IV $\log k_o$ for C2X and $\log k_p$ for C4X have been tabulated for the methyl, chlorine and iodine substituents. The influence of the steric effect calculated from these figures has been expressed in kcal/mole. Values for C4I have been calculated from the general rate equation in section III.5 since this compound has not been measured*.

T a b l e IV
Estimation of the steric effect of ortho substituents
in the isomerization of ortho-substituted stilbenes

Substituent	T(°C)	$\log k_o$	$\log k_p$	$-2.303 RT \log (k_o/k_p)$ (in kcal/mole)
Cl	120	0.349	0.959	1.095
	100	-0.339	0.250	1.002
	90	-0.715	-0.121	0.985
	70	-1.545	-0.877	1.046
} mean: 1.03				
CH ₃	100	0.005	0.650	1.098
	90	-0.371	0.300	1.111
	70	-1.173	-0.451	1.129
} mean: 1.11				
I	120	0.115	0.86	1.336
	100	-0.585	0.20	1.336
	90	-0.970	-0.16	1.344
	80	-1.375	-0.53	1.364
} mean: 1.35				

In table V these steric factors (in kcal) have been tabulated together with the van der Waals radii and the steric parameters E_s which have been determined by Taft^{24a,26} from the rates of the acid-catalyzed

* The value of ΔE_I^\ddagger has been calculated from:

$$\Delta E_I^\ddagger = 0.6 \Delta E_I^\ddagger = 0.6 \times 2.303 \times R \times 353 \times \log 1.8.$$

hydrolysis of o-substituted benzoates. It is seen from the table that the steric effect parallels the van der Waals radius and the steric parameter E_S .

T a b l e V
Steric effect of ortho substituents, van der Waals radii (in Å)
and steric parameters E_S

Substituent	H	Cl	CH ₃	I
Steric effect	0	1.03	1.11	1.35
v.d.Waals radius	1.2	1.80	2.0	2.15
E_S		+0.18	0.00	-0.20

III.7 UNCATALYZED THERMAL ISOMERIZATION

For all cis-stilbene derivatives blank experiments have been carried out to see whether spontaneous isomerization occurred when iodine was not present. In most cases no isomerization occurred. Spontaneous isomerization rates, different from zero are listed in table VI.

T a b l e VI
Thermal isomerization rate constants

T(°C)	Stilbene	k(h ⁻¹)
120	C3Br	0.007
120	C3I	0.005
120	C3tBu	0.007
120	C2I	0.006
100	C4OCH ₃	0.008
90	C4OCH ₃	0.001
120	C3,5Br ₂	15-30

In most cases the spontaneous isomerization rate is only 2-3% of the catalyzed reaction rate but the value found for C3,5Br₂ is extremely

high and exceeds the iodine-catalyzed rate by a factor 100! Nevertheless the catalyzed isomerization rate is proportional to the square root of the iodine concentration and also fits in the Hammett line.

In order to explain this remarkable behaviour it might be assumed that iodine totally inhibits the spontaneous isomerization. Another possible explanation is that in C3,5Br₂ an impurity is present which is an extremely good catalyst for cis-trans isomerization. This impurity must then have been removed by iodine. In order to test this hypothesis we let a solution of C3,5Br₂ in carbon tetrachloride react with iodine (0.04 mole/l) at 120°C. After five minutes the reaction mixture was cooled and washed with sodium thiosulphate solution. After drying over magnesium sulphate the C3,5Br₂ solution was again warmed to 120°. The thermal isomerization rate had now dropped to 0.15-0.20 h⁻¹. Thus it was concluded that an impurity did indeed cause the high isomerization rate.

This result makes it dubious whether a correction has to be applied for spontaneous isomerization in other cases. Although the thermal isomerization rates of other compounds tabulated in table VI are very low and would result in only a small correction, a test could be made in the case of C2I since the correction there would be about 8%.

The iodine-catalyzed isomerization rate of C 2I is proportional to the square root of the iodine concentration. If these rates are corrected by subtracting the spontaneous isomerization rate from the observed rate the proportionality between rate and concentration of catalyst no longer holds. It is therefore probable that in this case also the thermal isomerization does not occur in the presence of iodine.

For other stilbenes the thermal isomerization rate was only 2-3% of the catalyzed reaction rate. Thus, considering the above results it seems unlikely that a correction has to be applied and, consequently, in no case was the observed iodine-catalyzed isomerization rate corrected for thermal isomerization.

CHAPTER IV

DISCUSSION

IV.1 ENERGY SCHEME OF THE REACTION

In fig. 1 an energy diagram is presented as proposed by Visscher and Kooyman^{10,11} for iodine-catalyzed isomerizations of *cis*-cinnamic esters. A similar energy diagram will be valid for the isomerization of the stilbenes.

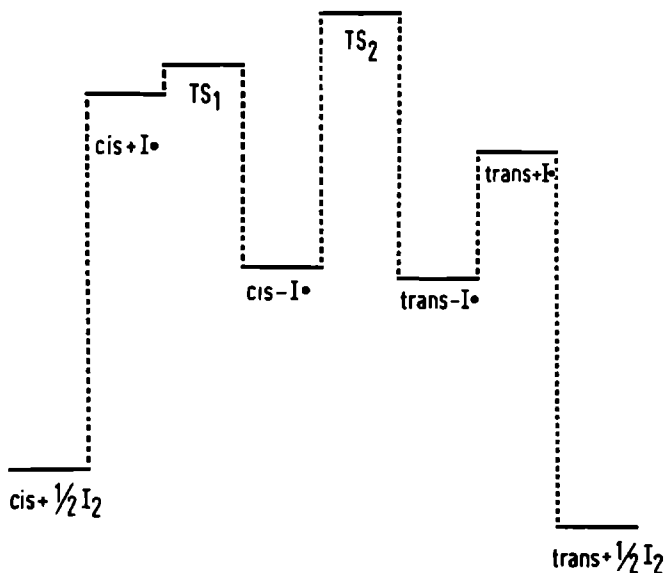


Figure 1

Energy diagram for isomerization of *cis*-stilbene

cis = *cis*-stilbene

TS₁ = transition state for addition of the iodine atom to *cis*

cis-I• = intermediate (see fig. 2 in section III.2)

TS₂ = transition state for rotation of *cis*-I• to the isomeric *trans*-I•

trans = *trans*-stilbene

In accordance with the experiments by Noyes and coworkers⁵ on di-iodoethylene it was concluded by Visscher and Kooyman that the rotation

is the rate-determining step in the isomerization reaction. If we make the same assumption in the case of the stilbenes the observed k value equals $K_1^{1/2} K_1 k_2$ and the measured activation energies tabulated in table III of section III.4 concern the energy difference between the initial state (cis + 1/2 I₂) and the transition state for rotation of the intermediate (TS₂).

However, a comparison between diiodoethylene and styryl-type olefins such as stilbene and cinnamic acid is dangerous. The addition of an iodine atom to the double bond of the cis compound which is endothermic to an extent of about 7 kcal in the case of ethylene (see introduction) is exothermic in the case of cis-stilbene because here the resulting benzyl-type radical is stabilized by resonance. The energy level of the intermediate will therefore be lower than that of (cis + I·). Hence the iodine atom is more firmly bound to cis-stilbene than it is to (diiodo)ethylene and its dissociation may require a greater activation energy which will lead to a smaller value of k_{-1} .

If this decrease in k_{-1} is not accompanied by a sufficiently great decrease in k_2 in the case of cis-stilbene, the attack of iodine atoms on the double bond might become the rate-determining step. Thus, it has been found by Benson, Egger and Golden^{15,16} that in the isomerization of cis-butene-2 under the influence of iodine atoms the rotation about the single bond in the intermediate radical is rate-determining, whereas in the iodine-catalyzed isomerization of pentadiene-1,3 the attack of iodine atoms is rate-controlling because the intermediate allyl-type radical is stabilized by resonance.

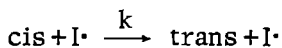
If k_1 was rate-determining; in our case the measured activation energies would concern the energy difference between (cis + 1/2 I₂) and the transition state for addition of the iodine atom to cis-stilbene (TS₁).

The greater part of the activation energy is consumed in the dissociation of iodine molecules into atoms. This dissociation requires 36.1 kcal in the gas phase. If we assume that this dissociation energy has the same value in apolar solvents then the isomerization of cis-stilbene derivatives under the influence of iodine atoms requires only $E_a - (1/2 \times 36.1) = 3.2 - 5.4$ kcal depending on the substituents of cis-stilbene (see table III of section III.4).

The value found for cis-stilbene (3.6 kcal) is identical to the activation energy found by Cauzzo and coworkers¹⁴ for the isomerization of cis-stilbene in n-hexane by iodine atoms which were produced photochemically. The close agreement may be fortuitous, however, and in reality the activation energy of 3.6 kcal may be considered as a maximum value since in other cases somewhat greater differences in acti-

vation energy between thermal and photochemical isomerization have been found (see table II in section I.3). Considering the accuracy of the measurements, however, the activation energy of 3.6 kcal will be at most 1 kcal too high.

The concentration of iodine atoms in the experiments of Cauzzo et al. was calculated from data of Meadows, Rosman and Noyes^{27,28} and found to be $1.9 \pm 0.1 \times 10^{-9}$ mole/l. The results were expressed as $k = k_{\text{obs}}/[I\cdot]$ and are therefore equal to the bimolecular rate constant of the reaction:



For cis-stilbene it was found that $k = 7.2 \times 10^4$ l mole⁻¹sec⁻¹ at 25°. The frequency factor of the rate constant is obtained from:

$$7.2 \times 10^4 = A e^{-3.6/RT}$$

giving: $\log A = 7.5^*$. Since the activation energy of 3.6 kcal is supposed to be a maximum value the same should be true for this value of $\log A$. It is nevertheless markedly smaller than the $\log A$ factor calculated by Benson, Egger and Golden¹⁵ for the attack of iodine atoms on the double bond of cis-stilbene (k_1).

These authors calculated $\log A$ factors for k_1 and k_{-1} from the equilibrium constant K_1 which was estimated from thermodynamic data. They estimated the addition of an iodine atom to cis-stilbene to be 5 kcal exothermic. The equilibrium constant K_1 was calculated to be:

$$K_1 = 10^{-3.0} \times 10^{5/2.3RT} \text{ l/mole.}$$

The $\log A$ factor for k_{-1} which is an unimolecular bond breaking was taken as 13. This value seems to be general for this type of reaction^{29a}. The $\log A$ factor of k_1 must therefore be 10 in good agreement with the value predicted by Frost and Pearson^{29b} for the reaction between an atom and a non-linear molecule ($\log A = 9-10$).

Benson et al.¹⁵ also calculated the $\log A$ factors of k_1 for attack of an iodine atom on cis- and trans-diiodoethylene in a similar way. They found them to be 9.8 in good agreement with experimental data. For iodine exchange of cis- and trans-diiodoethylene⁵, in which the attack of iodine atoms on the double bond is rate-determining, $\log A$ factors have been found of 9.4 and 9.6 respectively.

It is clear that the $\log A$ factor found for the isomerization of cis-stilbene is considerably lower than both the calculated and the experimental values found for the addition of iodine atoms to cis-stilbene and to the diiodoethylenes. *The results obtained for iodine-catalyzed iso-*

* Units of all A values in section IV.1 are: moles, litres, sec.

merization of cis-stilbene are therefore inconsistent with a mechanism in which the attack of iodine atoms on the double bond is rate-determining.*

We will therefore compare the results with a mechanism in which the rotation step is rate-determining. The observed bimolecular rate constant k is then equal to $k_1 k_2/k_{-1}$. The log A factor is:

$$\log A = \log A_1 - \log A_{-1} + \log A_2$$

$$7.5 = 10 - 13 + \log A_2$$

$$\log A_2 = 10.5.$$

This value is of the same order of magnitude as the $\log A_2$ factor found by Benson et al. for the rotation of the intermediate in the iodine-catalyzed isomerization of butene-2 ($\log A_2 = 11.2$) and the NO-catalyzed isomerization of pentadiene-1,3 ($\log A_2 = 11.5$).

The experimental $\log A_2$ value for the rotation of the sec-butyliodide radical has been compared by Benson with a calculated one obtained from:

$$A_2 \approx \frac{1}{2\pi} \left(\frac{RT}{2\pi I} \right)^{1/2}$$

I is the moment of inertia for the rotation of the ethylidene radical. A_2 was found to be $10^{11.3} \text{sec}^{-1}$. The $\log A_2$ factor for rotation of the intermediate in the case of cis-stilbene must be lower since the moment of inertia for rotation of the benzyl radical is greater than that of the ethylidene radical. Therefore our results seem to be consistent with a mechanism in which the rotation step is rate-determining.

This supposition may be corroborated further by the following reasoning. Additions of bromine atoms to ethylene and acetylene are exothermic reactions. It has been found that these processes require no activation energy in the gas phase^{30,31}. The bromine exchange of dibromoethylene with bromine atoms also proceeds with zero activation energy⁴. Therefore the activation energy for the addition of an iodine atom to the double bond of cis-stilbene, which is also an exothermic reaction, will be low and possibly zero. In section IV, 2C it is shown that the observed activation energy of 3.6 kcal is a reasonable value for the energy difference between TS_2 and (cis+I•). Thus the energy level of TS_2 may be somewhat higher than that of TS_1 . That k_2 is much smaller than k_{-1} is then not only due to the greater frequency factor of k_{-1} but also to the lower

* The calculated values of k_1 for cis-stilbene were compared by Benson and coworkers¹⁵ with Yamashita's data¹² ($\log A = 10.3$, $E_a = 25 - 18 = 7$ kcal). From these results it was concluded that k_1 is rate-determining in the case of cis-stilbene. The results of Yamashita are inaccurate, however, and the conclusion should be considered as erroneous.

activation energy of this step in comparison with k_2 .

By virtue of this discussion we consider the assignment of the rotation as the rate-determining step in the isomerization of *cis*-stilbenes as definitely settled.

IV.2 EFFECTS OF SUBSTITUENTS

It has been found that rate differences between the various substituted *cis*-stilbenes are due to a variation in activation energy. Thus the substituents influence the energy level of TS_2 since the measured activation energies apply to the difference in energy between this and the initial state (*cis*+ $1/2 I_2$).

There is no indication as to how substituents influence the energy level of the intermediate *cis*-I \cdot . So it remains uncertain whether substituents exert their influence on the reaction rate via the equilibrium constant K_1 for transformation from (*cis*+I \cdot) to *cis*-I \cdot or via the rate of rotation of the intermediate radical (k_2) or both *. If the variation of the energy level of *cis*-I \cdot is equal to that of TS_2 the substituent influences K_1 only, k_2 being constant. If the variation of the energy level of *cis*-I \cdot relative to (*cis*+I \cdot) is negligible the substituent influences k_2 only and K_1 is independent of substitution. In general a third possibility is, that substituents influence the energy level of TS_2 and, in a different way, also the level of *cis*-I \cdot and the substituent effects concern both K_1 and k_2 .

By stating what the essential differences are between the intermediate and the transition state TS_2 it may be possible to forecast which of the measured effects of substituents on the energy level of TS_2 will be likely to exert the same influence on the level of *cis*-I \cdot .

The rotation of the intermediate *cis*-I \cdot can take place in two different ways. It can proceed via opposition of phenyl group and iodine atom or via opposition of the two phenyl groups. Because of the greater steric requirements of the phenyl group in comparison with the iodine atom it may be accepted that rotation occurs via the former as indicated in fig. 2 (solid arrow).

* We have tried to determine K_1 independently for a number of *cis*-stilbene derivatives by measuring the concentration of the intermediate radicals by means of electron spin resonance. The reaction mixture failed to give any signal, however, even under strong illumination.

Apparently, the radical concentration during the reaction remains too small for detection by this method.

TS₂ can then be visualized as a structure, in which the iodine atom, C_α, C_β and the phenyl ring are just in plane.

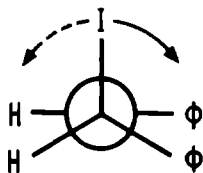


Figure 2

Rotation of the intermediate probably occurs via opposition of iodine atom and phenyl group (solid arrow)

If it is assumed that the increase in energy of the transition state over the intermediate is only caused by the steric resistance of phenyl group and iodine atom, this increase would be equal for all substituted stilbenes since, except for C3tBu, no steric effect of substituents on the isomerization rate has been found. This would mean that the energy difference between cis-I· and TS₂ would not be influenced by substituents and the measured differences in activation energy for various substituted stilbenes should be equal to the differences in energy of the corresponding intermediates. These energies could then be obtained by subtracting a constant, but unknown, quantity from the measured activation energies. Substituents would then only influence K₁ while k₂ would be equal for all compounds.

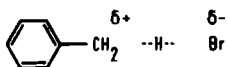
However, in this consideration no account is taken of possible differences in mesomeric and inductive effects of substituents on the intermediate and the transition state respectively. These effects will be discussed in more detail in the following sections.

A The inductive effect

Polar influences in radical reactions as they become apparent in ρ values different from zero have been related by Russell³² to the structure of the transition state. If the transition state is very similar to the initial state which is the case in the abstraction of an α -hydrogen atom from toluene by the highly reactive chlorine atom, the inductive effect found is best described by effects of the substituents on the electron density of the reaction site*. In the chlorination of substituted toluenes

* In a later article Russell and Williamson³⁵ reported a reinvestigation of the chlorination of substituted toluenes with chlorine and light. A better fit with σ^+ than with σ was reported. Thus the ρ value (-0.66) was also ascribed to charge separation. It seems probable therefore that all ρ values different from zero must be attributed to charge separation, the correlation with σ^+ or σ being dependent on whether the transition state resembles a benzyl cation or not.

correlation of the logarithms of the relative reaction rates with σ yielded ρ values -0.76 and -1.5 for chlorination with chlorine and light³³ and with sulphuryl chloride³⁴ respectively. If the transition state resembles more the final state the inductive effect can be ascribed to charge separation. In the bromination of toluene, for instance, considerable bond breaking has already occurred in the transition state which is polar in nature owing to the electrophilic character of the bromine atom. Since in the transition state for bromination of toluene a fractional positive charge is located on the α -carbon atom which can show resonance interaction with suitable para substituents a correlation with σ^+ holds³⁶.



ρ values for bromination of substituted toluenes obtained from $\rho\sigma^+$ correlations are -1.1 and -1.36, about -1.5 and -1.46 for bromination with Br_2 , N-bromo-succinimide and related compounds and BrCCl_3 respectively^{2c,37-41}.

We have found a ρ value of -1.21 at 100° for the isomerization of symmetrically substituted cis-stilbenes. A correlation with σ holds although resonance stabilization in the case of para substituents (see IV.2B) suggests that the transition state is similar to the final state for addition of an iodine atom to the double bond. That a correlation with σ^+ does not hold might be explained by the fact that the fractional positive charge is located on a saturated carbon atom and resonance stabilization is hence impossible (see fig. 2 in section III.2). In accordance with the arguments of Russell the inductive effect found in the isomerization might be attributed to charge separation due to the formation of the polar C-I bond. Since in the intermediate the C-I bond has already been completely formed this part of the substituent effect would affect the energy of cis- I^\cdot and TS_2 to an equal extent. The distance of the two energy levels would not be influenced by the inductive effect of the substituents and so the rate of rotation would be independent of polar effects.

However, it might be possible that the inductive effect has some influence on bond bending and stretching which occurs during the rotation.

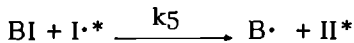
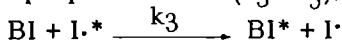
Polar effects can influence the rates of reactions in which only a rotation around a single C-C bond is of importance as is demonstrated by the effects of substituents on the rates of racemization of optically active biphenyls. Adams and coworkers^{24b,42} studied the rates of racemization of optically active 2-methoxy, 2'-nitro, 6'-carboxydiphenyls substituted in the 4 and 5 position. On plotting $\log k$ of racemization against the σ value of the substituent a rough linear relationship is found with a ρ value of about -1.

We therefore split the observed ρ value into ρ_1 valid for K_1 and ρ_2

for the rotation:

$$\rho = \rho_1 + \rho_2$$

ρ_1 will originate from charge separation due to the formation of the C-I bond whereas ρ_2 gives the susceptibility of the rotation to polar effects. An attempt to estimate the value of ρ_1 on the basis of other radical reactions can be made. The fact that our ρ value is of the same order of magnitude as the ρ values found for bromination of toluene with different reactants seems to suggest that the observed ρ value is a reasonable estimate for ρ_1 . A more quantitative comparison can be made with a ρ value found for the iodine exchange of benzyl iodide since this reaction involves the rupture of a C-I bond. Gardner and Noyes⁴³ measured the exchange rate of radioactive iodine (I^*) with substituted benzyl iodides (BI). They determined a quantity N_p for different benzyl iodides which is proportional to: $(k_3 + k_5)$. The k 's are related to the reactions:



It appeared that N_p was enlarged by the electron-withdrawing p-nitro group and diminished by the electron-donating p-methyl group. Application of the Hammett equation gave $\rho = +1.1$. This ρ value was attributed to the polarity of the C-I bond in benzyl iodide. A greater ρ_1 value is to be expected for the equilibrium constant K_1 since a second substituent is present in the symmetrically substituted stilbenes. On extrapolation of the graph of ρ vs. $-\frac{1}{T}$ (see fig. 3 in section III.3) to the measuring temperature used by Gardner and Noyes (30°) a ρ value of -1.6 is found. Since this value is of the order of magnitude which might be expected for ρ_1 it is probable that ρ_2 is small and that the inductive effect of substituents has little effect on the rate of rotation of the intermediate radical.

Of course both ρ values have opposite signs since in the iodine exchange reaction a C-I bond is broken whereas in the equilibrium preceding rotation in the isomerization reaction this bond is formed.

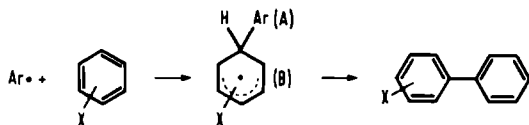
It should be mentioned, however, that the reliability of the ρ value for iodine exchange of benzyl iodide is not too great, since only three compounds were measured and also the extra resonance stabilization of the p-nitrobenzyl radical might contribute somewhat to the slope of the Hammett line.

B The resonance stabilization of the transition state by para substituents

Deviations from a linear relationship between $\log k$ vs. σ shown by

para-substituted stilbenes appear to be dependent on the nature of the parasubstituents. They are imperceptibly small for C4CH₃ and C4OCH₃, small for C4Cl and considerable for C4CN and C4NO₂. If these deviations had to be ascribed to resonance stabilization due to conjugation of the para substituent with a positive charge it would have been expected that C4CH₃ and C4OCH₃ in particular would deviate strongly and a better correlation would be obtained using σ^+ values. This does not appear to be the case. We have therefore ascribed these deviations to resonance stabilization of the transition state due to conjugation of the para substituent with an odd electron (i.e. extra resonance stabilization by the para substituent of the benzyl-type radical, see fig. 2 in section III.2). According to Walling^{2d} electron-supplying groups contribute little to radical stability but radical stabilization by electron-withdrawing groups roughly parallels their electron-withdrawing ability in the para position.

Resonance stabilization of radical intermediates has also been found to affect the rates of homolytic phenylation of benzene derivatives. In the homolytic phenylation reaction a phenyl radical, generated from a peroxide, substitutes a hydrogen atom of a benzene derivative via the formation of an intermediate σ -complex:



The relative reactivities of the various positions in the benzene derivatives towards phenyl radicals are expressed in partial-rate-factors (p.r.f.). They give a measure of the reactivity of these positions compared with the reactivity of any carbon atom of benzene itself. The p.r.f.'s are determined in competitive experiments. Phenyl radicals are generated in a 1:1 mixture of benzene and a substituted benzene (ϕ X). The amounts of diphenyl, o- $\phi\phi$ X, m- $\phi\phi$ X and p- $\phi\phi$ X formed are measured and corrected for their statistical weight. So p.r.f.'s are calculated from:

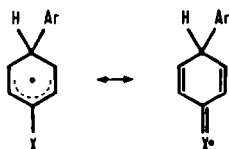
$$k_o/k = 3 \frac{[o-\phi\phi X]}{[\phi_2]} \quad k_m/k = 3 \frac{[m-\phi\phi X]}{[\phi_2]} \quad k_p/k = 6 \frac{[p-\phi\phi X]}{[\phi_2]}$$

Williams⁴⁴ determined p.r.f.'s for phenylation at 80°C. For the meta position p.r.f.'s are almost unity irrespective of the polar nature of the substituent, indicating that there is no preference for the phenyl radical to attack the meta position of a substituted benzene or any carbon atom

of benzene itself. It may therefore be concluded that the phenyl radical is a neutral species showing no preference for positions of high or low electron density.

Itô and coworkers⁴⁵ came to the same conclusion in their study on homolytic phenylation using substituted phenyl radicals generated from *p*-substituted *N*-nitrosoacetanilides. On plotting the logarithm of the *p.r.f.* for the meta position against the σ value of the substituent of the attacked benzene derivative straight lines were obtained. ρ values, calculated by the method of least squares are -0.81 for *p*-nitrophenylation, -0.27 for *p*-chlorophenylation, 0.05 for phenylation, 0.03 for *p*-methylphenylation and 0.09 for *p*-methoxyphenylation. It appears from these figures that both the phenyl and the *p*-methylphenyl radical are neutral species.

Partial rate factors for the para position are always higher than unity. This has been ascribed to extra resonance stabilization of the transition state by the para substituent. This transition state closely resembles the intermediate arylcyclohexadienyl radical:



Since the phenyl radical is a neutral species one may conclude that the reactivity of the para position towards phenyl radicals is controlled mainly by the degree to which the substituent can stabilize the transition state by conjugation with the odd electron. The logarithm of the *p.r.f.* for phenylation of the para position may therefore be used as a measure of the radical-stabilizing capacity of the substituent.

For arylations of the para position with substituted phenyl radicals Itô⁴⁵ found the following relation to hold:

$$\log(k_p/k) = \rho \sigma_p + \tau_p$$

The ρ values are those determined from arylation of the meta positions whereas τ_p is the logarithm of the *p.r.f.* for homolytic phenylation of the para position since ρ is about zero for phenylation.

We can treat our data obtained with para-substituted stilbenes in a similar fashion. τ_p is then equal to the deviation ($\Delta \log k_X$) from the Hammett line found for the para-substituted compound. $\Delta \log k_X$ and $\log(k_p/k)$ can be expressed in energy terms by means of formulas:

$$\Delta E_X^i = -2.303 R T \Delta \log k_X$$

$$\Delta E_X^\phi = -2.303 R T \log(k_p/k)$$

in which ΔE_x^i and ΔE_x^ϕ are equal to the lowering of the activation energies of the isomerization and phenylation reactions respectively as a consequence of resonance stabilization of the transition states by X. In table I ΔE_x^i values calculated from the deviations from the Hammett line are tabulated.

T a b l e I
The decrease of the activation energy for isomerization
of symmetrically p-substituted cis-stilbenes
due to resonance stabilization of the transition state (in kcal/mole)

T(°C)	ΔE_{Cl}^i	ΔE_{CN}^i	$\Delta E_{NO_2}^i$	$\Delta E_{CH_3}^i$	$\Delta E_{OCH_3}^i$
120°	-0.27	-0.81	-0.72	-0.05	-0.05
100°	-0.17	-0.81		0	0
90°	-0.17	-0.87		0	0
70°	-0.20			0	0
mean	-0.20	-0.83	-0.72	~ 0	- 0

T a b l e II
Partial-rate-factors for homolytic phenylation of benzene derivatives
(ϕX), and corresponding ΔE_x^ϕ values (in kcal/mole)

X	Williams (80°)		Itô (20°)		mean	
	k_p/k	ΔE_x^ϕ	k_p/k	ΔE_x^ϕ	ΔE_x^ϕ	ΔE_x^i
CH ₃ O			1.29	-0.15	-0.15	~ 0
CH ₃	1.4	-0.24	1.27	-0.14	-0.19	~ 0
Cl	1.6	-0.33	1.48	-0.23	-0.28	-0.20
CN	6.5	-1.31			-1.31	-0.83
NO ₂	6.6	-1.32	9.05	-1.28	-1.30	-0.72

In table II these values are compared with p.r.f.'s for homolytic phenylation of the para positions of the corresponding benzene derivatives and the equivalent ΔE_x^ϕ values. It appears that the substituents of C4CH₃ and C4OCH₃ which do not deviate from the Hammett line in the

isomerization reaction have small p.r.f. values. p-Cl with a somewhat greater p.r.f. gives rise to a small deviation of C4Cl. However, p-CN and p-NO₂ which show great p.r.f. values cause considerable deviations from the linear relationship of C4CN and C4NO₂. The influences of the substituents on the activation energies of both reactions (ΔE_X^i and ΔE_X^ϕ) parallel each other. This suggests strongly that deviations from the Hammett line for iodine-catalyzed isomerization of p-substituted cis-stilbenes are caused by extra resonance stabilization of the transition state due to conjugation of the substituent group with the odd electron.

C The absolute value of ΔE_X^i

The extra resonance stabilization of the cyclohexadienyl radical by para substituents will be greater than the observed ΔE_X^ϕ which is related to the resonance stabilization of the transition state. In this state the bond between the two phenyl groups has not yet been fully formed and consequently the odd electron is located less on phenyl group B in the transition state than in the intermediate cyclohexadienyl radical (see figures in the preceding section).

For a similar reason the extra resonance stabilization in the isomerization reaction of cis-stilbenes will be larger in the intermediate cis-I· than in a transition state like TS₁. However, the measured activation energies probably apply to the transition state TS₂ in which state the C-I bond is completely formed. That the value of ΔE_X^i is nevertheless still smaller than ΔE_X^ϕ (ΔE_X^i is about 0.6 ΔE_X^ϕ) can be understood as follows: The resonance energy of a benzyl residue will be dependent on whether the phenyl ring is in the plane of the methylene group or not and this will also be the case with the extra resonance energy of a para substituent. The degree of interaction between phenyl group and α -carbon atom will be proportional to the overlap of the 2p_z orbitals of the α -carbon atom and carbon atom 1 of the phenyl group. According to Coulson⁴⁶ this overlap is proportional to cos θ in which θ is the angle to which the phenyl group has been twisted out of the plane of the methylene group. From study of molecular models it appears that in the iodine-catalyzed isomerization of cis-stilbenes θ may be zero in the intermediate cis-I· but will show strongly increased values during the rotation step, reaching a maximum in TS₂ when iodine atom and phenyl group are opposed (fig.3).

It would be possible to calculate the value of θ in the transition state TS₂ from the experimentally obtained ΔE_X^i values if the values of the extra resonance energies by para substituents of the benzyl radical

were known. However, sufficiently accurate data of the relevant substituents are not available from experiments. Szwarc⁴⁷ measured bond dissociation energies of C-H bonds of the methyl group in methyl-substituted aromatic molecules. The difference between these dissociation energies and the dissociation energy of the C-H bond in methane (102 kcal) was ascribed to resonance stabilization of the resulting benzyl-type radical. The resonance energies obtained in this way are about 25 kcal for the benzyl radical and seem to be a few kcal higher for the p-methylbenzyl (26-27 kcal) the β -naphthylmethyl (27-28 kcal) and the α -naphthylmethyl radical (27-28 kcal). However, the resonance energy of the benzyl radical as determined from $D(C_6H_5CH_2-H)$ is dubious since other values for this dissociation energy are reported in the literature.

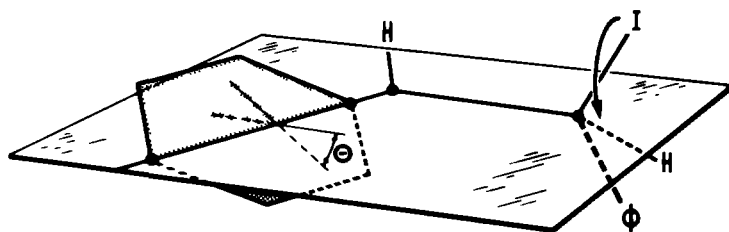


Figure 3

The resonance stabilization of the benzyl-type radical will diminish during the rotation since the phenyl ring is forced out of plane

Kerr⁴⁸ considers 85 kcal as a reliable value for $D(C_6H_5CH_2-H)$ on the basis of experiments of Price⁴⁹, Esteban and coworkers⁵⁰, and Walsh and coworkers⁵¹. Since the dissociation energy of methane was reported by Kerr to be 104 kcal/mole, the resonance energy of the benzyl radical would be about 19 kcal. Unlike Szwarc's data this value is in close agreement with the resonance energy of the benzyl radical calculated by Wheland^{52a} by means of a corrected molecular orbital method (15 kcal). In these calculations β was given the value of -38 kcal which is most consistent with the experimental resonance energies of aromatic molecules.

Wheland also calculated the resonance energies of the p-phenylbenzyl radical (16.5 kcal) the β -naphthylmethyl radical (16.5 kcal) and the α -naphthylmethyl radical (18.5 kcal). The extra resonance energies due to introduction of p-C₆H₅ or to condensation with a second benzene ring as in the β - and α -naphthylmethyl radicals (β -C₄H₄ and α -C₄H₄ substituents) are therefore 1.5, 1.5 and 3.5 kcal respectively. The reliability of these calculated values is shown by the close parallelism with the ΔE_x^\ominus values of these substituents which can be calculated from the partial-

rate-factors for homolytic phenylation of the corresponding benzene derivatives⁴⁴ (diphenyl, para position, p.r.f. = 3.4, $\Delta E_{\text{p-C}_6\text{H}_5}^{\phi} = 0.85$; naphthalene, β position, p.r.f. = 3.5, $\Delta E_{\beta\text{-C}_4\text{H}_4}^{\phi} = 0.86$; naphthalene, α position, p.r.f. = 16, $\Delta E_{\alpha\text{-C}_4\text{H}_4}^{\phi} = 1.95$).

This proportionality is to be expected on the basis of the results mentioned in section IV.2B.

From these $\Delta E_{\text{X}}^{\phi}$ values the $\Delta E_{\text{X}}^{\text{i}}$ values of the corresponding substituents can be calculated ($\Delta E_{\text{X}}^{\text{i}} = 0.6 \Delta E_{\text{X}}^{\phi}$).

$$\Delta E_{\text{p-C}_6\text{H}_5}^{\text{i}} = 0.5 \text{ kcal} \quad \Delta E_{\beta\text{-C}_4\text{H}_4}^{\text{i}} = 0.5 \text{ kcal} \quad \Delta E_{\alpha\text{-C}_4\text{H}_4}^{\text{i}} = 1.2 \text{ kcal}$$

These values are three times smaller than the calculated stabilizing effects of the same substituents on the benzyl radical.

Owing to the use of parameters which are not known exactly (i.e. β and the $\Delta E_{\text{X}}^{\text{i}}/\Delta E_{\text{X}}^{\phi}$ ratio) the reliability of the values found is not very high. Nevertheless a value of -0.3 seems to be a suitable estimate for the ratio of the stabilizing effect of a para substituent in the isomerization of cis-stilbene derivatives and that of the same substituent in the planar benzyl radical.

If we ascribe this diminished stabilization to the non-planarity of the benzyl-type radical in TS_2 it follows according to Coulson⁴⁶ that $\cos \theta \approx 0.3$ and $\theta \approx 70^\circ$. If, according to Fischer-Hjalmar⁵³, the resonance energy is taken as proportional to $\cos^2 \theta$ a θ value of about 65° results. Finally, Adrian⁵⁴ calculated the resonance energies of diphenyl, cis-stilbene and the triphenylmethyl radical. In these calculations the resonance energies are reduced to 30% of those of the planar molecules if the phenyl rings are twisted only about 45° out of plane.

A θ value of 65° - 70° is in good agreement with the value predicted from molecular models. Using Stuart molecular models the maximum value of θ during the rotation is about 75° - 80° . This maximum angle is reached when iodine atom and phenyl group are opposed. However, molecular models do not take into account the possibility of bond bending which might relieve the loss of resonance stabilization by preservation of a flatter structure in TS_2 . The actual value of θ in TS_2 may therefore be somewhat lower and 45° and 70° may be considered as lower and upper limits.

In section IV.1 the energy level of the transition state was calculated to be 3.6 kcal above the energy of (cis + I \cdot). To reach the transition state TS_2 first an olefinic π -bond is broken during the formation of the C-I

bond. With simple olefins this process is about 7 kcal endothermic as is mentioned in section I.1. With *cis*-stilbenes, the first step would be even more endothermic due to the loss of the resonance energy of *cis*-stilbene (2.3 kcal^{53b}). However, the product is a benzyl-type radical which is strongly stabilized by resonance (about 19 kcal) and the energy of the intermediate may be about 10 kcal lower than that of (*cis* + I·). In TS₂ about 70% of the resonance energy is lost due to the non-planarity of the benzyl-type radical. Thus the energy is raised by about 13 kcal to pass the transition state reaching a maximum value quite consistent with the experimental one.

It is mentioned in section IV.1 that the energy difference between the transition state TS₁ and (*cis* + I·) is small and possibly zero. Thus this energy difference is much smaller than the energy difference between TS₁ and the intermediate *cis*-I· as here the first step is exothermic to an extent of about 10 kcal. On the basis of Hammond's postulate⁵⁵ we may therefore conclude that TS₁ resembles (*cis* + I·) very much. Hence it is to be expected that structural variations of *cis*-stilbene (such as the introduction of substituents) exert only a little influence on the rate of attack of iodine atoms on the double bond (k_1). The rather great effects of substituents found are to be interpreted as influences on k_{-1} (and k_2). Since these rate constants do not play a role in the reaction rate expression when k_1 is rate-determining we reach the same conclusion as already drawn from the analysis of frequency factors (IV.1) viz. the rotation is the rate-determining step.

IV.3 THE DEVIATION OF C3tBu FROM THE HAMMETT LINE

Apparently the *tert.*-butyl group hinders the isomerization to a certain extent* since C3tBu deviates from the Hammett line in a negative sense. These deviations ($\Delta \log k$) are presented in table III.

T a b l e III
Deviations of C3tBu from the Hammett lines (in log k units)

T(°C)	120°	100°	90°	70°	mean
$\Delta \log k$	-0.200	-0.225	-0.220	-0.200	-0.21

* It must be noted that in the iodine-catalyzed isomerization of *cis*-cinnamic esters the *tert.*-butyl ester shows the largest reaction rate^{10,11}. This has been explained as due to the increase of the internal energy of the *cis* compound by the bulky *tert.*-butyl group. Apparently such an increase in internal energy does not play a role in C3tBu.

The isomerization rate of C3tBu is about 60% of the value which would make it fit into the Hammett line. We would like to ascribe the low value to a steric effect of the bulky tert.-butyl group which can be explained as follows: Phenyl ring A of the intermediate will be in plane with the central C-C bond as much as possible in order to obtain maximal resonance stabilization of the benzyl residue. There are two possibilities for a meta substituent on this phenyl ring, position 3 ('endo' position, fig. 4a) and position 5 ('exo' position, fig. 4b).

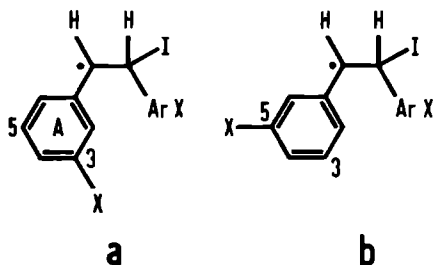


Figure 4

Two possible conformations of the intermediate for isomerization of symmetrically meta-substituted cis-stilbenes

If it is assumed that the intermediates with endo and exo substituents are always in rapid equilibrium, the rotation rate can be described by means of the Winstein-Holness⁵⁶ equation:

$$k_2 = N_{\text{endo}} k_{\text{endo}} + N_{\text{exo}} k_{\text{exo}}$$

in which N_{endo} and N_{exo} are the mole fractions of endo and exo intermediate ($N_{\text{endo}} + N_{\text{exo}} = 1$) and k_{endo} and k_{exo} the rates of rotation of the respective intermediates.

Steric factors will not influence the value of k_{exo} since X remains too remote from the iodine atom during the rotation. k_{endo} will not be influenced by X as long as X is small but when X is the bulky tert.butyl group steric interaction between tert.butyl group and iodine atom may occur. The endo tert.butyl group requires a greater value of θ in TS₂, which causes an extra decrease in resonance energy and raises the energy level of TS₂ for rotation of the intermediate. As a result rotation of the intermediate with the endo tert.butyl group will be relatively slow.

In the above explanation the lowering of the reaction rate by the tert.-butyl group is not due to an increase in the energy of the transition state. The rotation of the exo intermediate will require the normal activation energy. However, since rotation of one of the two possible conformations

of the intermediate is hindered the chance that isomerization occurs is diminished. Hence it is to be expected that the A factor of the isomerization rate constant will be lowered. In accordance with this expectation it is found that the activation energy has a value corresponding to the σ value of the m-tert.-butyl group, whereas the A factor is lowered to a degree just exceeding the experimental error (see section III.4).

Another argument in favour of the explanation given might be provided by the isomerization rate of 3,5,3',5'-tetra-tert.-butyl-cis-stilbene. In this compound a tert.-butyl group is always present in endo position, hence this substance should show a very low isomerization rate.

The observed hindering by m-tert.-butyl groups might provide an additional argument in favour of the conclusion that the rotation is the rate-determining step in the isomerization reaction. The tert.-butyl groups in C3tBu are too remote from the ethylenic double bond to hinder the approach of the iodine atom. Their retarding effect cannot therefore be made consistent with a mechanism in which this step is rate-determining.

IV.4 IODINE-CATALYZED CIS-TRANS ISOMERIZATION OF STYRYLPYRIDINES AND CIS-STILBENE

The investigation by Gauzzo and coworkers¹⁴ on the iodine-catalyzed photochemical isomerization of cis-stilbene has been referred to before. As has already been mentioned, the concentration of iodine atoms in their experiments was calculated to be $1.9 \pm 0.1 \times 10^{-9}$ mole/l. The results were expressed as $k = k_{\text{obs}}/[I\cdot]$ and are therefore equal to the isomerization rate at unit iodine atom concentration. For cis-stilbene it was found that $k = 7.2 \times 10^4 \text{ l mole}^{-1}\text{sec}^{-1} = 2.7 \times 10^8 \text{ l mole}^{-1}\text{h}^{-1}$ at 25°. Since the activation energy found was 3.6 kcal the reaction rate constant would be $9 \times 10^8 \text{ l mole}^{-1}\text{h}^{-1}$ at 100°. We have found a rate constant of $2.77 \text{ l}^{1/2}\text{mole}^{-1/2}\text{h}^{-1}$ at 100°. The iodine atom concentration in solution* at 100° may therefore be estimated to be $\approx 3 \times 10^{-9}$ mole/l at unit concentration of iodine molecules. The dissociation constant of iodine is then $\approx 10^{-17}$ mole/l in excellent agreement with the value of K_I given by Benson¹⁵:

$$K_I = 10^{3.4} 10^{-35.4/2.3RT} = 10^{-17.2} \text{ (100°C).}$$

The same authors measured isomerization rates of 4-substituted

* We have found that the reaction rate is not changed if the solvent carbon tetrachloride is replaced by paraffin oil.

3'-styrylpyridines¹⁴. They correlated the logarithms of the reaction rate constants with σ^+ values of the substituents and found a ρ value -0.3. A measurement for the 4-iododerivative was excluded because this value did not fit in the linear relationship. However, we think it more rational to exclude the measurements of the 4-nitroderivative because of the great radical-stabilizing capacity of this substituent. The remaining measurements should be correlated with σ and a ρ value of -0.7 is then found. It is of interest to note that this ρ value is about half our ρ value (-1.6 at 25°) whereas the deviation of the 4-nitroderivative is about 0.3 log k units (0.53 units at 25° in our case).

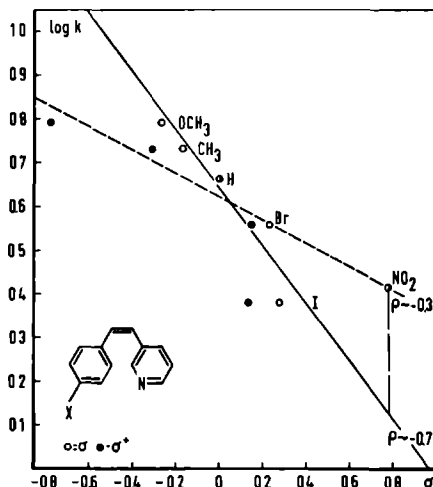


Figure 5

Plot of log k, for isomerization of 4-substituted 3'-styrylpyridines under the influence of photochemically generated iodine atoms, against σ and σ^+ . Data from ref.14 are used.

CHAPTER V

IODINE-CATALYZED ISOMERIZATIONS OF PARA-METHOXY-CIS-STILBENES AT ROOM TEMPERATURE; HIGH ORDER REACTIONS

V.1 DEVIATIONS IN THE BEHAVIOUR OF C₄OCH₃ AT HIGH IODINE CONCENTRATIONS

In the tables in section III.1 no rate constants are listed for C₄OCH₃ at iodine concentration 0.02 mole/l. When we tried to make measurements at this concentration results were obtained which were at first sight inconsistent. A run was made at 90°C by mixing equal volumes of a solution of C₄OCH₃ and an iodine solution of 0.04 mole/l in reaction tubes. The tubes were sealed off after the air had been swept out with purified nitrogen*. The contents of the tubes were kept at room temperature during the operations. At time $t = 0$ the tubes were heated to 90°C.

From concentration measurements at different times a first order plot was obtained which indicated, however, that at $t = 0$ about 20% of the cis compound had already been converted to T₄OCH₃ (fig. 1). Furthermore, from the slope of the line a k value of 4.1 was calculated which was markedly greater than the k value at 90° with iodine concentrations of 0.005 and 0.001 mole/l ($k = 2.55$ and 2.54 respectively).

At the last iodine concentrations C₄OCH₃ appeared to behave normally. At temperatures of 100°, 90°, and 70° normal first order plots were obtained which did not deviate from zero at $t = 0$. The slopes of these lines indicated that the reaction rate was proportional to the square root of the iodine concentration. This was not the case, however, at 70° where the k value obtained with an iodine concentration of 0.005 mole/l ($k = 0.65$) was markedly higher than the value obtained at a concentration of 0.001 mole/l ($k = 0.43$).

* This method for the exclusion of oxygen proved to give almost identical k values as the procedure described in section II.5 which was applied to all other measurements. In the case of C₄OCH₃ the iodine solution and the cis-stilbene solution were kept separate during the cooling, however, since we were afraid that the solid iodine which separates during cooling might give rise to a very rapid isomerization.

The deviations in the behaviour of C4OCH₃ can be explained by the assumption that in this compound the isomerization can also be realized via a different mechanism. The intercept at t=0 found for the reaction at 90° with an iodine concentration of 0.02 mole/l may then be ascribed to a rapid reaction via this mechanism even at room temperature and the greater rate constants at 90° and 70° to a contribution of this mechanism to the reaction rate under these circumstances.

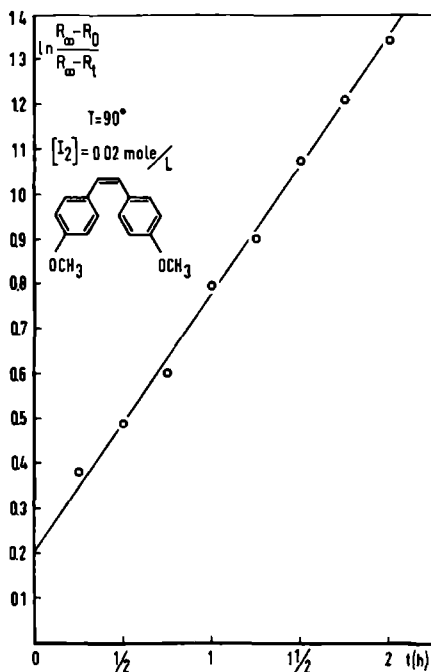


Figure 1

First order plot for isomerization of C4OCH₃ at iodine concentration 0.02 mole/l. At time $t=0$ about 20% of the cis compound has already been converted to T4OCH₃.

From our data it seems that isomerization via this alternative mechanism is not greatly influenced by temperature but will be strongly dependent on the iodine concentration.

V.2 KINETIC INVESTIGATIONS AT ROOM TEMPERATURE*

In order to investigate the remarkable behaviour of C4OCH₃ mentioned in the preceding section kinetic measurements were performed at 40°,

* The measurements were carried out mainly by Drs. G.H.L. Nefkens.

25° and 5°C. On extrapolation of the Arrhenius plot for isomerization via the normal 'iodine atom mechanism' it appears that the reaction rate via this mechanism is negligible at these temperatures. Reaction rates were measured for cis-trans isomerization of C4OCH₃ at iodine concentrations of 0.02, 0.015, 0.01 and 0.005 mole/l. For comparison similar measurements were performed on C3OCH₃ and 4-monomethoxy-cis-stilbene (CMS) at iodine concentrations of 0.04, 0.02 and 0.01 mole/l. Like all other compounds C3OCH₃ did not isomerize at these temperatures.

Table I

T(°C)	n	[I ₂]x10 ³	k _{min}	k	k _{max}	s
Rate constants of 4,4'-dimethoxy-cis-stilbene Solvent: carbon tetrachloride						
40	7	20	0.43	0.53	0.63	0.11
40	8	15	0.18	0.21	0.24	0.033
25	5	20	0.41	0.51	0.61	0.081
25	6	20	0.52	0.59	0.66	0.067
25	8	15	0.19	0.20	0.21	0.014
25	7	10	0.041	0.046	0.051	0.0056
25	6	10	0.041	0.046	0.052	0.0062
25	6	5	0.0049	0.0062	0.0075	0.0013
5	7	20	0.66	0.70	0.73	0.036
5	8	15	0.26	0.27	0.285	0.014
5	6	10	0.055	0.060	0.065	0.0048
5	6	5	0.0059	0.0064	0.0069	0.00047
Rate constants of 4-monomethoxy-cis-stilbene Solvent: carbon tetrachloride						
5	8	40	1.85	1.98	2.11	0.16
5	5	20	0.11	0.14	0.17	0.023
5	5	10	0.0128	0.0122	0.0116	0.00045

Table II

Rate constants of 4-monomethoxy-cis-stilbene in carbon tetrachloride at 0°C. Iodine concentration 0.02 mole/l

n	[cis] ₀	k _{min}	k	k _{max}	s
8	0.25	0.16	0.17	0.185	0.013
6	0.025	0.19	0.20	0.21	0.010

T a b l e III
Rate constants of 4-monomethoxy-cis-stilbene

T(°C)	n	[I ₂]x10 ³	k _{min}	k	k _{max}	s
Solvent: chloroform						
0	5	40	20.0	20.5	21.0	0.44
0	5	20	1.88	1.94	2.00	0.050
Solvent: acetic acid						
25	5	40	15.4	15.8	16.2	0.030
25	5	20	1.95	2.01	2.07	0.050
25	5	10	0.271	0.279	0.287	0.060
42	5	10	0.37	0.40	0.44	0.029

The headings in the tables I, II and III are:

n = number of measurements

[I₂] = iodine concentration in mole/l

k = mean value of the n observed k_i values expressed in h⁻¹. k is a pseudo first order constant, derived from: $-d[\text{cis}]/dt = k[\text{cis}]$.

k_{min}^{max} = 95% confidence limits of k

s = standard deviation

[cis]₀ = initial concentration of cis-stilbene derivative (≅ 0.05 mole/l, unless otherwise stated)

In tables I, II and III the observed reaction rates are tabulated as pseudo first order constants since the reaction rate appeared to be first order with respect to cis-stilbene (see fig. 2 and table II). In preliminary experiments it was established that oxygen did not influence the reaction rate. Therefore the precautions to exclude oxygen taken for the measurements at higher temperatures could be omitted here. Nevertheless the measurements were carried out in carbon tetrachloride which was purified as described in section II.1.

It is seen from the table that the temperature coefficient of the reaction rate at constant iodine concentration has a low, probably negative value. This temperature dependence is consistent with an activation energy of about -2 kcal/mole.

The rate is, however, strongly dependent on the iodine concentration. A twofold increase in this concentration causes a tenfold increase in the isomerization rate of C4OCH₃ while the rate of CMS is even more strongly dependent on the iodine concentration.

In figs. 3a, b and c the logarithms of the reaction rate constants in

carbon tetrachloride have been plotted against the logarithms of the iodine concentration. The slopes of the obtained lines show that the reaction order with respect to iodine is about 3.5. This order seems to be somewhat lower for C4OCH₃ at 25°, but higher for CMS at 5°.

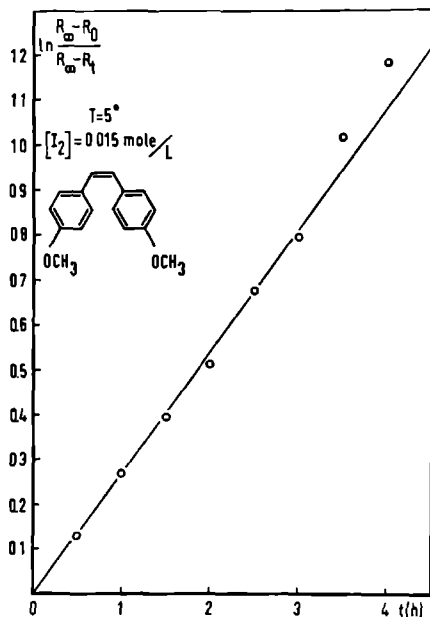
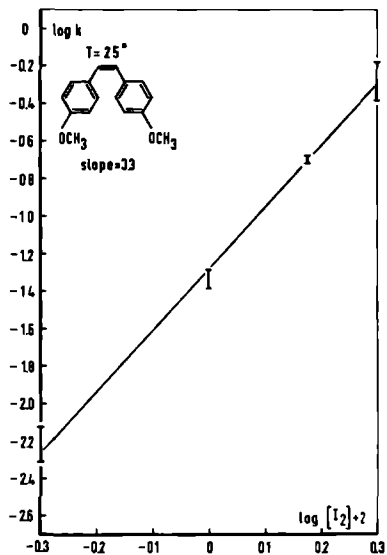


Figure 2
First order plot for isomerization of C₄OCH₃ at 5°C

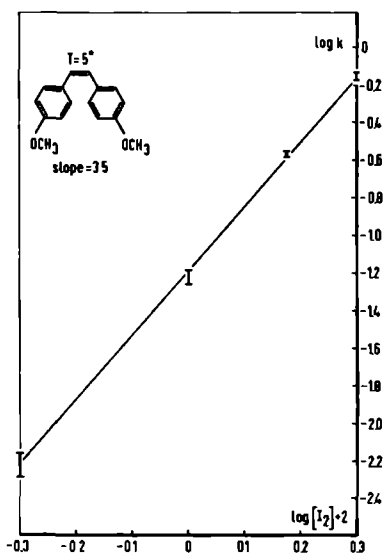
Replacement of the non-polar solvent by chloroform or acetic acid causes an increase in reaction rate at constant iodine concentration. The order with respect to iodine decreases with increasing polarity of the solvent. For CMS the order is 3.7 in carbon tetrachloride solution. In chloroform solution it has dropped to 3.5 and in acetic acid to 2.9. The activation energy has been raised to +3 kcal/mole in the last solvent (see table III and fig. 3d).

V.3 MECHANISM OF THE REACTION

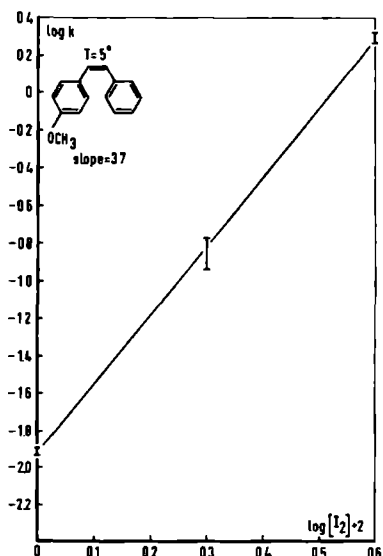
Reactions which are of high order with respect to halogen have also been observed in halogen substitution and addition reactions in apolar solvents. Table IV gives a survey of examples reported in the literature. It is notable that these reactions have always been investigated at



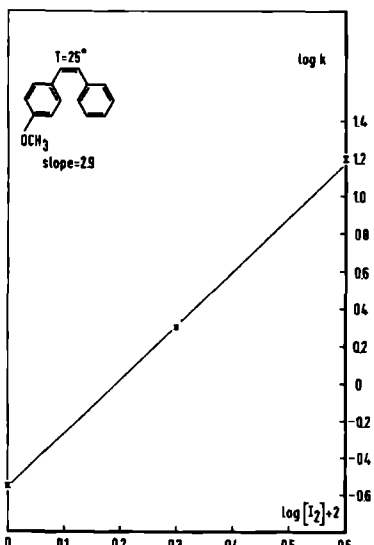
a. Solvent: carbon tetrachloride



b. Solvent: carbon tetrachloride



c. Solvent: carbon tetrachloride



d. Solvent: acetic acid

Figures 3 a,b,c and d
The logarithms of the pseudo first order constants for isomerization
of para-methoxy-cis-stilbenes as a function of the logarithms
of the iodine concentrations,
The slopes of these lines are equal to the order with respect to iodine.

Table IV
High order reactions of halogens

Reactants	Substrate	Reaction	Solvent	Temp. (°C)	E _a (in kcal)	Rate Law	References
Br ₂ +I ₂	benzene	bromination	benzene	25°		v=k[h _{alogen}] ⁴	57
Br ₂ +I ₂	phenanthrene	bromination	CCl ₄	25°		v=k[ArH][Br ₂] ³ [I ₂] ^{5/2}	58,59,60
Br ₂ +I ₂	mesitylene	bromination	CCl ₄	24°		v=k[Br ₂] ² [IBr] ² + + k' [Br ₂] [IBr] ³	
						v=k[ArH][Br ₂] ² [IBr] + + k' [ArH] [Br ₂] [IBr] ²	61
Br ₂ +I ₂	toluene	bromination	CCl ₄	25°		v=k[C ₆ H ₅ CH ₃ ,Br ₂][IBr] ³	62
Br ₂ +IBr	mesitylene	bromination	CCl ₄	14°-36°	-0	v=k [ArH] [Br ₂] [IBr] ²	63
Br ₂ +I ₂	ethyl cinnamate (A)	bromine addition	CCl ₄	24°		v=k[A][Br ₂] ² [IBr]	64
Br ₂	allyl benzoate (AB)	bromine addition	CCl ₄	24°-42°	+4	v=k[AB][Br ₂] ³	65
Br ₂	AB	bromine addition	CHCl ₃ ; C ₆ H ₅ Cl	24°-42°	-0	v=k[AB][Br ₂] ²	65
ICl	anisole; acetanilide	iodination	acetic acid	24°-50°	10-15	v=k [ArH] [ICl] ²	66
ICl	m-xylene	iodination	mixture	20°		v=k [ArH] [ICl] ³	67
ICl	mesitylene; C ₆ H(CH ₃) ₅	iodination	CCl ₄	25.2°-45.7°	-1.6; -1.4	v=k [ArH] [ICl] ³	68,69
ICl	toluene; p-xylene	iodination	trifluoro- acetic acid	1.6°-25.2°	12.7	v=k [ArH] [ICl]	68,69
Br ₂	toluene; xylene	bromination	CH ₃ NO ₂ ; C ₆ H ₅ NO ₂	5°-35°	4	v=k [ArH] [Br ₂] ³ [RNO ₂]	70
Br ₂	mesitylene	bromination	acetic acid + H ₂ O	16.4°-25.4°	6.8	v=k [ArH] [Br ₂] + + k' [ArH] [Br ₂] ²	71

room temperature or thereabouts. The reactions were all third or fourth order with respect to halogen when a non-polar solvent was used (in most cases carbon tetrachloride!). When measured, the temperature dependence was small and in some cases consistent with a slightly negative activation energy. Replacement of the apolar solvent by a more polar one caused a decrease in reaction order in the case of bromine addition to allyl benzoate⁶⁵ (solvents chloroform or chlorobenzene). In the iodination of aromatics with iodine monochloride the order with respect to halogen dropped from three in carbon tetrachloride solution to two in acetic acid solution and the reaction became first order with respect to halogen if trifluoroacetic acid was used as solvent.* An increase in activation energy with polarity of solvent was observed in this reaction⁶⁸.

Our isomerization reaction shows many of the characteristics of the reported reactions. We think therefore that the rate-determining steps of the isomerization reaction and the halogen addition and substitution reactions are very similar in nature.

Andrews and Keefer⁶⁸ have given an explanation of the high order with respect to halogen for reactions in apolar solvents.

We cite:

'To promote the electrophilic attack of halogen on an aromatic molecule in a non-aqueous solvent a third reactant, the function of which is to weaken the halogen-halogen bond, seems commonly to be required. In non-polar solvents an aggregate of several halogen molecules must fill this role, since reaction orders with respect to halogen are ordinarily high in such media. Indeed the iodine bromide catalyzed bromination of mesitylene in carbon tetrachloride appears to be exactly third (first in bromine and second in catalyst) order with respect to halogen⁶³. In acetic acid mesitylene reacts with bromine and with iodine monochloride by processes which are second order in halogen^{66, 71, 72}. In this solvent the over-all bromination reaction receives small contribution from a reaction which is first order in bromine and in which acetic acid itself probably functions as the required third reactant. This first-order term becomes tremendously more important when small amounts of water are added to the medium⁷³. It seems likely that the water, as does zinc chloride in acetic acid^{72, 74}, also enhances the first-

* We have also made an attempt to isomerize dimethoxy-cis-stilbene in trifluoroacetic acid but C_4OCH_3 rapidly reacts with the solvent. Probably the acid is added to the double bond since the U.V. spectrum of the oily reaction product shows no stilbene absorption. The absorption maximum (280 $m\mu$) is in the neighbourhood of the anisole absorption maxima (273 and 279 $m\mu$). See also ref.79.

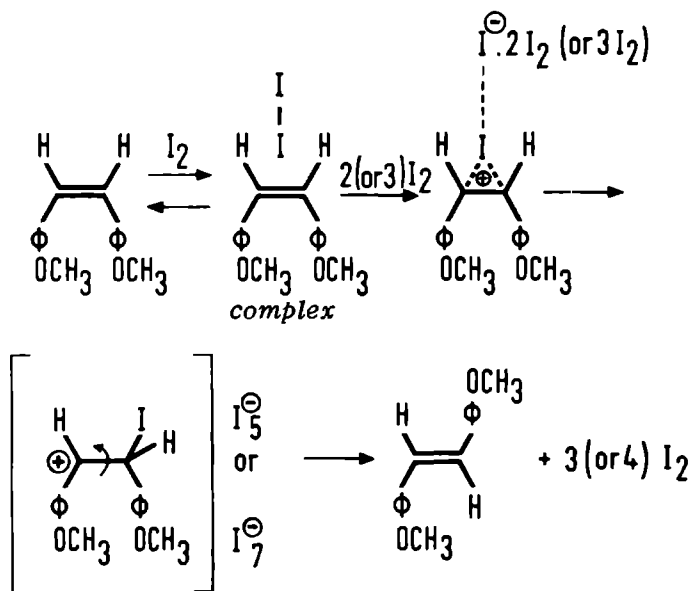
order reaction by direct participation in the rate-determining step rather than solely through the imposition of a favourable dielectric effect.¹

It has been proposed that in these halogenation reactions molecular complexes are formed between a molecule of halogen and aromatic compound and that more halogen molecules act as catalyst for a further reaction of the molecular complex (see also ref. 1b).

We will assume that in the isomerization reaction the first step of the reaction will also be the formation of a molecular complex:



The rate-determining step which follows will be the dissociation of this complex into cis-I^{\oplus} and I^{\ominus} . The absence of effects of oxygen on the reaction rate and its strong dependence on the nature of the solvent also suggest an ionic mechanism. This dissociation must then be catalyzed by two or three iodine molecules, which may even serve to 'pull' the iodide ion away from the iodine molecule in the molecular complex. Thus an I^{\oplus} ion is added to the double bond and a carbonium ion is formed with a single C-C bond around which rotation is possible. The whole series of reaction steps is depicted in the scheme:



The catalytic function of the iodine molecules can be understood if it is assumed that the transition state of the over-all reaction is very much like the cyclic iodonium ion or the more classical cis-I^{\oplus} ion in which the I^{\ominus} is bound to two or three iodine molecules.

It is known that the formation of I_3^{\ominus} from I^{\ominus} and I_2 is exothermic as has been explained as due to interaction of the iodide ion with the induced dipole in the iodine molecule⁷⁵. Even in water this process is 3.5 kcal exothermic although the solvation energy of the I^{\ominus} ion is lost here⁷⁵. Complex formation of the iodide ion with more iodine molecules will lead to a further decrease in the energy of the transition state*.

Reaction rates are not determined by activation energies but by free energies of activation ($\Delta F^* = \Delta H^* - T\Delta S^*$). Isomerization by this type of mechanism will therefore only be accelerated by complex formation with more iodine molecules if the decrease in activation energy (enthalpy) outweighs the decrease in activation entropy. In the case of C_4OCH_3 and CMS in carbon tetrachloride or chloroform this situation is reached if two or three molecules participate in complex formation (formation of I_5^{\ominus} and I_7^{\ominus}). Under these conditions a reaction with a low activation energy and a low frequency factor may be expected, as is indeed found ($E_a \approx -2 \text{ kcal}$, $A \approx 10^5 \text{ l}^{3.5} \text{ mole}^{-3.5} \text{ h}^{-1}$).

In more polar solvents complex formation will be more restricted as the formation of larger aggregates is accompanied by a loss of solvation energy (smaller ions are better solvated than larger ones). In this way it can be understood why the order with respect to iodine decreases with increasing polarity of the solvent.

A structure of the transition state as depicted above also explains that from all compounds investigated only derivatives with para methoxy groups can isomerize by this type of mechanism since the para methoxy group in particular can conjugate with a positive charge and therefore stabilize the ionic transition state. It is to be expected that p-(dimethyl)-amino-stilbenes will isomerize even more rapidly via this mechanism.**

Assuming that the concentrations of the intermediates are sufficiently small (see section V.4), the rate law corresponding to the proposed

* Goldman and Noyes⁷⁶ gave a similar explanation for the catalysis by iodine molecules in the rupture of the C-I bond which occurs in the iodine exchange of benzoyl iodide.

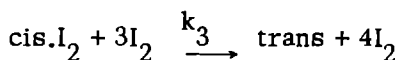
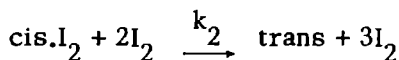
** *Note added in proof:*

Recent measurements by Mr. A.J.M. Berns on 4-dimethylamino-cis-stilbene show that this compound isomerizes already with traces of iodine. Pseudo first order constants in carbon tetrachloride solution at 21.5°C are about 2 and 11 h^{-1} at iodine concentrations of 10^{-5} and 2×10^{-5} mole/l respectively. The reactions were carried out in a 1 cm cuvette with a stilbene concentration of 10 mg/l.

mechanism is:

$$v = K_1 [\text{cis}] \left\{ k_2 [\text{I}_2]^3 + k_3 [\text{I}_2]^4 \right\} \quad (1)$$

k_2 and k_3 are rate constants for the reactions:



A graph of $\log v / [\text{cis}]$ against $\log [\text{I}_2]$ in formula (1) gives a curved line, the slope of which approaches three when $k_2 [\text{I}_2]^3 \gg k_3 [\text{I}_2]^4$ and four when the reverse is the case. When $k_2 [\text{I}_2]^3$ and $k_3 [\text{I}_2]^4$ are of comparable size the slope of the curve is about 3.5.

Thus our data are in accordance with equation (1). The accuracy of the measurements is insufficient to bring to light that the lines are strictly speaking curved. More accurate measurements especially over a wider range of iodine concentrations should be made to demonstrate this fact. The reaction times would become inconveniently short at high and long at low iodine concentrations, however, and the requisite accuracy will therefore probably be unobtainable. It is clear that different values of the broken order between 3 and 4 can conveniently be explained as due to variations in the ratio $k_2 [\text{I}_2]^3 / k_3 [\text{I}_2]^4$.

V.4 THE INFLUENCE OF COMPLEX FORMATION

In principle the high order with respect to iodine might also be caused in part by complex formation of iodine with stilbene. In general the iodine concentration to be used in any rate equation for the isomerization is equal to the concentration of *free* iodine. This may be different from the *total* iodine concentration which would be diminished by complex formation with cis- and trans-stilbene derivative. Assuming 1 : 1 complexes:

$$[\text{I}_2]_F = [\text{I}_2] - K_1 [\text{cis}]_F [\text{I}_2]_F - K_2 [\text{trans}]_F [\text{I}_2]_F$$

$$[\text{I}_2]_F = \frac{[\text{I}_2]}{1 + K_1 [\text{cis}]_F + K_2 [\text{trans}]_F}$$

in which $[I_2]_F$ is the concentration of free iodine and $[cis]_F$ and $[trans]_F$ the concentrations of free cis- and trans-stilbene derivative.

If K_1 and K_2 were high $[I_2]_F$ would be a small fraction of $[I_2]$ and very little iodine would be free to catalyze the isomerization. Since in our measurements at high iodine concentrations the iodine concentration is about equal to that of stilbene $[cis]_F$ and $[trans]_F$ would also be much smaller. Hence the concentration of free iodine would be disproportionately greater at high than at low $[I_2]$ i.e. $[I_2]_F$ varies more strongly than $[I_2]$ with a variation of the latter concentration. This fact would contribute to the slopes of the lines in figs. 3a, b, c and d and be a trivial cause of the high order.

We have made no measurements to determine K_1 or K_2 . These values may, however, be estimated as follows:

Laarhoven and Nivard⁷⁷ have determined constants of complex formation for complexes of stilbene derivatives with tetracyanoethylene in methylene dichloride at 20°. The results are expressed in K_x values i.e. concentrations are expressed in mole fractions instead of mole/l. K_x has been found to have values of 144 for 4,4'-dimethoxy-trans-stilbene, 28 for cis-stilbene and 23 for trans-stilbene. It is seen that dimethoxy-stilbene forms complexes which are about six times more stable than the complexes of unsubstituted stilbene.

Andrews and Keefer⁷⁸ measured the K_c value of complex formation between trans-stilbene and iodine. ($K_c = 0,31$ l/mole at 25° in carbon tetrachloride).

Using the K_x ratio found for the tetracyanoethylene complexes the K_c value of C_4OCH_3 and T_4OCH_3 will be about 1,5 l/mole. Monomethoxystilbene will form complexes which will be intermediate in stability between the complexes of stilbene and dimethoxystilbene. The K_c values of monomethoxystilbene (cis and trans) may therefore be estimated to be about unity.

Although the values are rather roughly estimated it may be concluded that the constants of complex formation will be too small to contribute to the slope of the lines in figs. 3a, b, c and d. At a stilbene concentration of 0,05 mole/l at most 10% of the iodine will be bound.

Other observations lead to a similar conclusion: If complex formation was the cause of the high order of the reaction the stilbene concentration would have a great effect both on the rate and the apparent order of the reaction which is not observed. The trans compound of dimethoxystilbene is poorly soluble in carbon tetrachloride. With concentrations as used a supersaturated solution of T_4OCH_3 is reached at about 5% conversion and crystallization sets in at about 20% conversion. From that moment

the stilbene concentration drops steadily as the reaction proceeds. The isomerization runs of C_4OCH_3 at 5° and iodine concentrations 0.02, 0.015 and 0.01 mole/l have been followed up to 78%, 70% and 84% conversion respectively. The pseudo first order constants obtained were found to be independent of the conversion percentage throughout the reaction as may be judged from the rather narrow confidence limits of the obtained k values (table I).

Assuming that the complex formation constants for CMS and TMS are about unity the concentration of free iodine becomes:

$$[I_2]_F = \frac{[I_2]}{1 + [\text{stilbene}]}$$

in which $[\text{stilbene}] = [\text{cis}] + [\text{trans}]$ and is therefore equal to the initial concentration of cis-stilbene derivative $[\text{cis}]_0$. The rate law (1) then becomes:

$$v = [\text{cis}] \left\{ \frac{k_2 [I_2]^3}{\{1 + [\text{stilbene}]\}^3} + \frac{k_3 [I_2]^4}{\{1 + [\text{stilbene}]\}^4} \right\} \quad (2)$$

According to this formula the reaction rate at a stilbene concentration of 0.025 mole/l will be twice the reaction rate at concentration of 0.25 mole/l.

It appears from table II, however, that the difference in reaction rate is only about 15% and scarcely exceeds the experimental error. It must therefore be concluded that either both free and complexed iodine can act as a catalyst for the conversion of the molecular complex with almost equal effectiveness* or that the complex formation constants are still smaller than unity.

Therefore equation (1) is in better agreement with the experimental results than equation (2).

* In the iodine bromide catalyzed bromination of mesitylene in carbon tetrachloride both free and complexed iodine bromide appear to react with equal effectiveness⁶³.

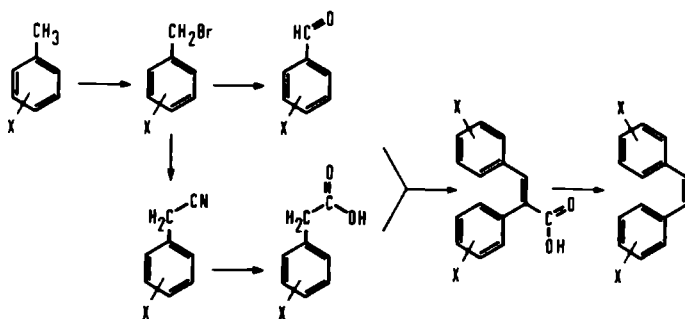
CHAPTER VI

SYNTHESES

In this chapter the preparation and purification of the stilbenes and other starting materials are described. Technical assistance was given by Miss G.J.J. van Heeswijk, Miss M.J.B.P.J. van Hooff and Miss J.M.C. van der Wielen. Microanalyses were carried out mainly by Mr. J. Diersmann. Melting points were measured with a Leitz Mikroskopheiztisch 350 and are uncorrected.

VI.1 REACTION SCHEME

A good and general route for the preparation of *cis*-stilbene derivatives applicable in all cases starts with the Perkin condensation of a substituted benzaldehyde and a substituted phenylacetic acid. The resulting substituted α -phenyl-*trans*-cinnamic acid is decarboxylated in quinoline at 230-235°C, using copper chromite as catalyst. The syntheses have been described manifoldly in the literature⁸⁰⁻⁹². Both the required benzaldehyde and the phenylacetic acid can be prepared from the corresponding benzyl bromide derivative which is obtained in general by direct bromination of a substituted toluene. The whole series of reactions used is presented in the reaction scheme:



VI.2 BENZYL BROMIDES

Bromination was carried out by adding 0.6 mole of bromine dropwise to 1.0 mole of the substituted toluene at such a rate that the reaction was completed in 1 hour. For toluenes having electron-donating substituents brominations could be performed in boiling carbon tetrachloride. Toluene derivatives with electron-attracting substituents reacted poorly at this temperature and brominations were carried out at higher temperatures without using any solvent. The stronger the electron-attracting power of the substituent the higher the temperature needed for the reaction to occur. Bromination of *m*-nitrotoluene could only be effected at 200°C. The reactions were accelerated by illumination with a 500 watt bulb. After bromination was completed the reaction mixture was fractionated. Yields calculated from the amount of bromine used vary from 50-80%. Physical constants of the benzyl bromides prepared are given in table I. All benzyl bromides except *m*-tert.-butylbenzyl bromide have strong lacrimatory properties. By far the strongest lacrimator is *o*-iodobenzyl bromide.

Table I
Physical constants of substituted benzyl bromides

Substituent	Boiling point (°C)		Melting point (°C)		Temp. of bromination (°C)
	found	lit. *	found	lit. *	
3Cl	74°-76°/1.5mm	103°-105°/8mm	-	-	120°
3NO ₂	119°/0.7mm	130°/3mm	58°	58°	200°
3Br	125°-129°/8mm	122°-124°/12mm	41°-43°	42.5°-43°	170°
3I	90°/3mm	-	47°-49°	49°-50°	150°
2CH ₃	103°/19mm	110°/20mm	17°	20°-21°	b.p.CCl ₄
3,5(CH ₃) ₂	91°/5mm	112°/15mm	37°	40°	b.p.CCl ₄
3,5Br ₂	92°-125°/0.7mm	-	85°-92°	92.2°-92.4°	170°
3tBu	87°/3mm	115.5°/8mm	75°-85°	-	180°
2I	116°-120°/2.5mm	125°/4mm	54.5°-56°	53°	200°

Other compounds synthesized:

m-methylbenzyl chloride from *m*-xylene with SO₂Cl₂ and dibenzoyl peroxide in CCl₄, b.p. 194°-197° (lit. 195°-197°).

m-nitrobenzyl chloride from *m*-nitrotoluene with SO₂Cl₂ and dibenzoyl peroxide in CCl₄, b.p. 109°/1.5 mm, m.p. 43°-45.5° (lit. b.p. 173°-174°/34 mm, m.p. 46°-47°). Yield only 10%.

o-iodotoluene from diazotized *o*-toluidine and KI, b.p. 75°/6 mm, $n_D^{25} = 1.6048$ (lit. b.p. 83°-84°/14-15 mm, $n_D^{20} = 1.6030$).

m-iodotoluene from diazotized *m*-toluidine and KI, b.p. 87°-89°/13 mm (lit. 84°/

* Literature values are from Beilstein, 'Handbuch der Organischen Chemie' or from Hodgman, 'Handbook of Chemistry and Physics', unless otherwise stated.

13 mm).

m-tert.-butyltoluene from toluene, tert.-butyl chloride and aluminum chloride. The resulting mixture of meta- and para-tert.-butyltoluene was separated by converting them to the sulphonic acids with concentrated sulphuric acid. The sulphonic acid of m-tert.-butyltoluene was separated in the form of its sodium salt by means of NaCl. (Shoosmith and McGechee⁹³ separated the barium salt by means of barium carbonate but this procedure is much more laborious and does not give better results.) Desulphonization was then performed by boiling with 50% sulphuric acid from which the m-tert.-butyltoluene was distilled with steam, b.p. 56°/4 mm, $n_D^{25} = 1.4924$ (lit. b.p. 189°, $n_D^{25} = 1.4921$).

3,5-dibromotoluene by bromination of o-toluidine and subsequent deamination by means of diazotization and boiling with ethyl alcohol, m.p. 35°-37° (lit. 36.8°-37°).

VI.3 BENZALDEHYDES

Benzaldehydes were prepared from benzyl bromides by the Sommelet reaction using hexamethylenetetramine as reagent as in the preparation of α -naphthaldehyde⁹⁴. Benzaldehydes, prepared by this reaction are tabulated in table II. Yields were about 60%.

T a b l e II
Physical constants of substituted benzaldehydes

Substituent	Boiling point (°C)	
	found	lit.
3Cl	51°- 54°/1 mm	84°-86°/8mm
3tBu	86°/5 mm	-
3,5(CH ₃) ₂	75°/2.5mm	220°-222°
3,5Br ₂	120°-155°/6.5mm	-
2CH ₃	84°/20 mm	195.5°
2I	75°/2.5mm	129°/14mm(ref.99)

The following benzaldehydes have been prepared from starting materials other than benzyl bromides.

m-methoxybenzaldehyde from m-hydroxybenzaldehyde by methylation with dimethyl sulphate according to Posner⁹⁵, b.p. 122°-126°/25 mm (lit.⁸⁷ 126°-127° 25 mm).

m-nitrobenzaldehyde by nitration of benzaldehyde, b.p. 102-105/0.1 mm. It was recrystallized from chloroform: petroleum ether at -80°, m.p. 52°-54° (lit. 58°-59°).

m-bromobenzaldehyde from m-nitrobenzaldehyde by reduction and a subsequent Sandmeyer reaction, b.p. 110°/15 mm (lit. 90°-92°/4 mm).

m-iodobenzaldehyde was prepared in poor yield from *m*-nitrobenzaldehyde by reduction with Sn and HCl, diazotization and treatment with potassium iodide solution, m.p. 54° (lit.⁹⁶ 55°-56°). The cold solution of the diazonium compound is best added to the potassium iodide at 60° as mixing of the solutions at 0° may result in a severe explosion.

VI.4 PHENYLACETIC ACIDS

Most phenylacetic acids have been prepared from benzyl bromides by cyanation and subsequent hydrolysis. 0.5 mole of substituted benzyl bromide was dissolved in 500 ml of ethyl alcohol or dimethylformamide*. This solution was mixed with a solution of 0.6 mole of sodium cyanide in 50 ml of water. The mixture was refluxed for 4 hours, filtered and the filtrate evaporated. The resulting benzyl cyanide was hydrolyzed without initial isolation by refluxing with 50% sulphuric acid for 2 hours.

T a b l e III
Physical constants of substituted phenylacetic acids

Substituent	Melting point (°C)	
	found	lit.
3CH ₃	59,5°- 62,5°	60,5°-61,5°
3Cl	76,0°- 76,5°	77,5°-78,5°
3NO ₂	114°-115°	122°
3Br	100°-102°	100°
3I	130°-131,5°	129° (ref.100)
3tBu	liquid	-
3,5(CH ₃) ₂	94°-98°	100°
3,5Br ₂	124°-141°	-
2CH ₃	73°-81°	88°-89°
2Cl	95°-96°	95°-96°
2I	107°-111,5°	110°

After completion of the reaction the sulphuric acid was decanted and the phenylacetic acid which was dark in colour was recrystallized from 1 l of water as follows: The water was heated to boiling and the solid melted. After boiling for 5 minutes the flask was cooled in ice. At first a small amount of oil separated, but as soon as the

* The method of cyanation using alcohol-water or dimethylformamide-water as solvent proved to have advantages over the use of dimethylsulphoxide as solvent as has been done by Friedman and Schechter⁹⁷. Yields are better and purer products result. At 40° the reaction in DMSO proceeds only to a minor degree and on heating the reaction mixture to higher temperatures it turns black. This holds especially for benzyl bromides having an electron-attracting substituent. *m*-Nitrobenzyl cyanide cannot be prepared at all in DMSO.

temperature dropped to 10° - 20° below the m.p. of the phenylacetic acid derivative crystals appeared. At this moment the water layer was decanted and if necessary filtered to remove any oil drops floating on the surface. After further cooling to 10° crystals were filtered off. The filtrate was used for a repetition of the procedure. In this way by always using the same portion of water, all the phenylacetic acid derivative present could be obtained as a solid with a sharp melting point. The table shows some melting ranges of 4° . In these cases we omitted further purification by means of recrystallization from water since the materials were already sufficiently pure for the Perkin synthesis. The method of purification was not successful in the case of 3,5-dibromophenylacetic acid. Yields were about 60-85%.

The phenylacetic acids prepared in this way are listed in table III.

p-chlorophenylacetic acid has been prepared from *p*-chloroacetophenone by the Willgerodt reaction, m.p. 98° - 101° (lit. 106°).

p-cyanophenylacetic acid was prepared from *p*-aminophenylacetic acid by means of the Sandmeyer reaction according to Jaeger and Robinson⁹⁸, m.p. 150° - 153° (lit. 152°).

VI.5 STILBENE DERIVATIVES

Since most *cis*-stilbene derivatives have been prepared analogously to the synthesis of 4,4'-dimethoxy-*cis*-stilbene⁸⁹, the details of the preparations will not be given here. We shall deal only with the methods of purification which often differed for the various compounds. Decarboxylations of the α -phenylcinnamic acid derivatives were carried out in quinoline as described in section VI.1. After cooling, the reaction mixture was dissolved in ether and the quinoline removed by washing with 10% HCl. In most cases the ethereal solutions were dark brown in colour, even after treatment with decolourizing carbon. After evaporation of the solvent, the mixture was purified by elution chromatography on an alumina column (Woelm, activity grade 1). Petroleum ether of boiling range 60° - 80° was used as elution solvent in most cases. The dark-coloured impurities remained at the top of the column and a colourless mixture of *cis*- and *trans*-stilbene derivative was eluted. The yield of α -phenylcinnamic acid derivative was usually 50-60%. The yield of pure *cis*-stilbene derivative obtained therefrom was at most 50%.

Cis-stilbene has been prepared using the method of Buckles, Bremer and Wheeler⁸¹. From 41 ml of benzaldehyde and 55 g of phenylacetic acid 48 g of α -phenylcinnamic acid (m.p. 174° - 175.5°) was obtained. This was decarboxylated and the resulting *cis*-stilbene distilled three times and the fraction 145° - 146° /15 mm collected, $n_D^{20} = 1.6206$ (lit. $n_D^{20} = 1.6212$, b.p. 133° - 136° /10 mm).

Trans-stilbene. The commercial product was recrystallized from

ethyl alcohol and carbon tetrachloride. From the latter solvent trans-stilbene crystallizes in long needles containing carbon tetrachloride which is rapidly lost on drying. A white solid results, m.p. 125.5°-126.0° (lit.⁹⁰ 124°).

4,4'-dimethoxystilbene. After decarboxylation of α -(4-anisyl)-4-methoxycinnamic acid (m.p. 205°-210°) a mixture of C4OCH₃ and T4OCH₃ resulted. The mixture was treated with hexane in which T4OCH₃ dissolved poorly. It was recrystallized from carbon tetrachloride, m.p. 215.0°-215.3° (lit.¹⁰¹ 214°). The hexane solution was chromatographed using petroleum ether as elutant. After recrystallization from the same solvent C4OCH₃ was obtained as white crystals, m.p. 35°-36° (lit.⁸⁹ 35.5°-36°).

4,4'-dimethylstilbene. By decarboxylation of α -(4-tolyl)-4-methylcinnamic acid (m.p. 179.5°-181°) a mixture of C4CH₃ and T4CH₃ was obtained. This mixture was dissolved in petroleum ether and on cooling to -20° T4CH₃ crystallized out. It was recrystallized three times from carbon tetrachloride, m.p. 181°-182° (lit.¹⁰² 176°-177°). The mother liquor was evaporated and the resulting C4CH₃ distilled, b.p. 128°-138°/0.08 mm. The distillate was chromatographed with petroleum ether and recrystallized from ethyl alcohol, m.p. 39°-41° (lit.¹⁰³ 32.3°).

Analysis: C4CH₃ found: C = 91.9%, 92.3% H = 7.7%, 7.9%
 T4CH₃ found: C = 91.9%, 91.7% H = 7.7%, 7.8%
 calculated: C = 92.26% H = 7.74%

3,5,3',5'-tetramethylstilbene. The dark brown mixture resulting after decarboxylation was chromatographed with petroleum ether. A light yellow mixture of C3,5(CH₃)₂ and T3,5(CH₃)₂ was obtained. This mixture was dissolved in boiling ethyl alcohol. On cooling to room temperature T3,5(CH₃)₂ separated out. It was recrystallized from ethyl alcohol and sublimed in vacuo, m.p. 140°-141.5°. The mother liquor was further cooled to -40°. A yellow substance separated out and was rejected. The solution was now almost colourless and on further cooling to -80° C3,5(CH₃)₂ crystallized out. It was recrystallized four times from ethyl alcohol at -80°. A white solid was obtained (m.p. 31°-34.5°) consisting of C3,5(CH₃)₂ contaminated with about 1-2% trans compound.

Analysis: C3,5(C H₃)₂ found: C = 91.3%, 91.5% H = 8.6%, 8.7%
 T3,5(CH₃)₂ found: C = 91.6%, 91.5% H = 8.5%, 8.5%
 calculated: C = 91.47% H = 8.53%

3,3'-di-tert.-butylstilbene. α -(3-tert.-butylphenyl)-3-tert.-butylcinnamic acid was obtained as an oily product which only partly solidified. The mixture of C3tBu and T3tBu was chromatographed with petroleum ether. The solution was cooled in ice and T3tBu separated out. It was recrystallized from ethyl alcohol three times and sublimed in vacuo, m.p. 122.5^o-124^o. C3tBu was obtained as a colourless liquid on evaporation of the solvent, $n_D^{25} = 1.5565$.

Analysis: C3tBu found:	C = 89.9%, 90.0%	H = 9.6%, 9.6%
T3tBu found:	C = 90.6%, 90.7%	H = 9.6%, 9.7%
calculated:	C = 90.35%	H = 9.65%

3,3'-dimethylstilbene. The mixture obtained by decarboxylation of α -(3-tolyl)-3-methylcinnamic acid (m.p. 153.5^o-157.5^o) was chromatographed with petroleum ether. In this way complete separation of C3CH₃ and T3CH₃ appeared possible. C3CH₃ was first eluted and isolated by evaporation of the solvent. The homogeneity of the product was demonstrated by analysis, thin layer chromatography and N.M.R. spectroscopy, $n_D^{25} = 1.5977$. T3CH₃, next eluted, was recrystallized from hexane at -80^o, m.p. 60.3^o-60.7^o (lit.¹⁰² 55^o-56^o).

Analysis: C3CH ₃ found:	C = 91.8%, 92.2%	H = 7.6%, 7.6%
T3CH ₃ found:	C = 92.2%, 92.2%	H = 7.8%, 7.9%
calculated:	C = 92.26%	H = 7.74%

3,3'-dimethoxystilbene. After decarboxylation of α -(3-anisyl)-3-methoxycinnamic acid (m.p. 152^o-160^o) a brown mixture of C3OCH₃ and T3OCH₃ resulted. This mixture was purified by elution chromatography with benzene. C3OCH₃ and T3OCH₃ were then separated by dissolving them in hexane. On cooling to -80^o T3OCH₃ separated out, was filtered off and recrystallized from hexane, m.p. 97.8^o-98.5^o (lit.¹⁰⁴ 101^o). After evaporation of the solvent C3OCH₃ was distilled, b.p. 140^o-144^o/0.08 mm. Some isomerization occurred during distillation but T3OCH₃ proved to be insoluble in C3OCH₃. The former compound crystallized out and the liquid appeared to contain only C3OCH₃ as became evident from the U.V. spectrum. C3OCH₃, $n_D^{25} = 1.6103$.

Analysis: C3OCH ₃ found:	C = 80.1%, 80.1%	H = 6.8%, 6.9%
T3OCH ₃ found:	C = 79.8%, 79.9%	H = 6.8%, 6.9%
calculated:	C = 79.97%	H = 6.71%

3,5,3',5'-tetrabromostilbene. The dark-brown mixture obtained after

decarboxylation was purified by elution chromatography. C3,5Br₂ and T3,5Br₂ were separated by dissolving the mixture in boiling ethyl alcohol. On cooling to room temperature T3,5Br₂ separated out. It was sublimed in vacuo, recrystallized twice from a 1 : 1 mixture of ethyl alcohol and carbon tetrachloride and again sublimed, m.p. 213^o-214.5^o. No sufficient analytical data could be obtained from T3,5Br₂. By cooling the mother liquor to -80^o C3,5Br₂ was obtained and recrystallized three times from ethyl alcohol, m.p. 109^o-111.5^o.

Analysis: C3,5Br₂ found: Br = 65.1%, 65.2%
T3,5Br₂ found: C = 35.0%, 35.1% H = 1.7%, 1.8%
calculated: C = 33.91% H = 1.63% Br = 64.46%

3,3'-dichlorostilbene. The mixture resulting from decarboxylation of α -(3-chlorophenyl)-3-chlorocinnamic acid (m.p. 170.5^o-172.5^o) was chromatographed with petroleum ether. T3Cl was separated out on cooling the eluate to -80^o and was recrystallized from hexane, m.p. 96.5^o-97.0^o (lit.¹⁰⁵ 93.8^o-94.6^o). The residual solution was evaporated leaving C3Cl as a colourless oil, $n_D^{25} = 1.6264$.

Analysis: C3Cl found: Cl = 28.0%, 28.1%
T3Cl found: Cl = 28.4%, 28.4%
calculated: Cl = 28.46%

3,3'-dibromostilbene. After decarboxylation a dark-brown mixture of C3Br and T3Br was obtained. It was purified by elution chromatography using a 9 : 1 mixture of petroleum ether and benzene as elutant. After evaporation of the solvent the mixture was dissolved in boiling hexane. On cooling to -80^o T3Br separated out. It was recrystallized twice from carbon tetrachloride and sublimed in vacuo, m.p. 101.5^o-102.5^o (lit.¹⁰⁵ 52.8^o-53.4^o). By evaporation of the hexane solution C3Br was obtained as a colourless liquid, $n_D^{20} = 1.6532$, $n_D^{25} = 1.6507$.

Analysis: C3Br found: Br = 46.4%, 46.9%
T3Br found: Br = 47.5%, 47.6%
calculated: Br = 47.28%

3,3'-diiodostilbene. The mixture of C3I and T3I was chromatographed with petroleum ether: benzene = 9 : 1. By cooling the resulting colourless solution to -80^o T3I separated out. It was recrystallized from ethyl alcohol and sublimed in vacuo, m.p. 100.0^o-100.8^o (lit.¹⁰⁵ 91.4^o-92.0^o). C3I was further purified by preparative thick layer chromatography.

It was obtained as an almost colourless liquid which proved to be impure.

Analysis: C3I found: I = 53.6%, 53.9%
T3I found: I = 58.9%, 58.9%
calculated: I = 58.75%

4,4'-dinitrostilbene. α -(4-nitrophenyl)-4-nitrocinnamic acid was prepared as described by Ketcham and Jambotkar⁸³ but it did not give a clear melting point. It was decarboxylated and the resulting product extracted with chloroform at room temperature. The extract was chromatographed and the yellow C4NO₂ obtained from the eluate was recrystallized from chloroform, m.p. 186°-188° (lit.⁹⁰ 186°-187°). The yellow solid left behind in the extraction had a m.p. >300°. It was thought to be T4NO₂ as irradiation of a dilute chloroform solution gave rise to the formation of more C4NO₂.

4,4'-dichlorostilbene. The synthesis of α -(4-chlorophenyl)-4-chlorocinnamic acid (m.p. 175°-179°) was carried out analogously to the synthesis of α -(4-nitrophenyl)-4-nitrocinnamic acid⁸³. T4Cl dissolved poorly in hexane and was recrystallized from carbon tetrachloride, m.p. 178.5°-179° (lit.¹⁰⁶ 174°-175°). The hexane solution was evaporated and the impure C4Cl chromatographed with petroleum ether and recrystallized from the same solvent. It was obtained as large, transparent crystals of m.p. 40.0°-40.5°.

Analysis: C4Cl found: Cl = 28.3%, 28.3%
T4Cl found: Cl = 28.4%, 28.4%
calculated: Cl = 28.46%

4,4'-dicyanostilbene. α -(4-cyanophenyl)-4-cyanocinnamic acid (m.p. 202°-207°) was prepared analogously to α -(4-nitrophenyl)-4-nitrocinnamic acid⁸³. From the mixture obtained after decarboxylation C4CN was dissolved in carbon tetrachloride in which T4CN is almost insoluble at room temperature. Both C4CN and T4CN were recrystallized from carbon tetrachloride to which some aluminum oxide was added to adsorb coloured impurities. C4CN, m.p. 171°-172° (lit.¹⁰⁷ 152°-154°) and T4CN, m.p. 288.5°-289.5° (lit.¹⁰⁷ 282°-284°) were obtained as colourless compounds.

Analysis: C4CN found: N = 11.8%, 12.1%
T4CN found: N = 12.1%, 12.1%
calculated: N = 12.16%

3,3'-dinitrostilbene. From the mixture resulting after decarboxylation C3NO₂ was isolated by extraction with ether. The ethereal solution was evaporated and the resulting C3NO₂ twice chromatographed using chloroform as elutant for the first chromatographic separation and ethyl acetate:petroleum ether = 1 : 1 for the second. After evaporation of the solvent C3NO₂ was recrystallized from chloroform. The yellow compound gave a m.p. 85°-87°. T3NO₂ was purified by extraction of the impurities with acetone. It was sublimed in vacuo and obtained as a yellow compound having m.p. 261°-263° (lit.¹⁰⁸ 240°-242°).

Analysis: C3NO₂ found: C = 62.3%, 62.3% H = 3.8%, 3.9% N = 10.3%
 calculated: C = 62.22% H = 3.73% N = 10.37%

2,2'-dimethylstilbene. After decarboxylation of α -(2-tolyl)-2-methylcinnamic acid (m.p. 160°-168°) the dark-coloured mixture obtained was chromatographed with petroleum ether. On evaporation of the solvent white crystals of C2CH₃ were obtained which melted at 48°-51°. After recrystallization from ethyl alcohol the m.p. was 54°-56° (lit.¹⁰³ 56.4°). Since we could not detect the presence of T2CH₃ in the reaction mixture, this was prepared by irradiation of a solution of C2CH₃ and iodine in chloroform. When all C2CH₃ had been transformed into T2CH₃ the chloroform solution was washed with sodium thiosulphate solution and water and then dried over anhydrous calcium chloride. After evaporation of the solvent T2CH₃ was recrystallized from carbon tetrachloride and ethyl alcohol, m.p. 81.5°-82.5° (lit.¹⁰³ 81.7°).

Analysis: C2CH₃ found: C = 92.4%, 92.3% H = 7.9%, 8.0%
 T2CH₃ found: C = 92.2%, 91.8% H = 7.8%, 7.9%
 calculated: C = 92.26% H = 7.74%

2,2'-dichlorostilbene. The mixture which resulted after decarboxylation was purified by elution chromatography with petroleum ether. After evaporation of the solvent a white solid was obtained which was recrystallized once from hexane and twice from ethyl alcohol. It proved to be C2Cl and had a m.p. 63.5°-64.0°. T2Cl was obtained from C2Cl by isomerization with iodine as described for the previous compound. It was recrystallized from carbon tetrachloride and alcohol and sublimed in vacuo, m.p. 96°-97° (lit.¹⁰⁵ 96.4°-96.8°).

Analysis: C2Cl found: Cl = 28.5%, 28.6%
 T2Cl found: Cl = 28.4%, 28.3%
 calculated: Cl = 28.46%

2,2'-diiodostilbene. After decarboxylation of α -(2-iodophenyl)-2-iodocinnamic acid (m.p. 61° - 70°) the reaction mixture was chromatographed using benzene:petroleum ether = 1 : 9. The solution was evaporated, the remaining solid dissolved in boiling alcohol and then cooled to room temperature. A yellow by-product separated out which gave on recrystallization from alcohol a m.p. of 114° - 115° . C2I was obtained by cooling the alcohol solution to -80° . It was recrystallized twice from alcohol at -80° , once from alcohol at room temperature and three times from hexane at room temperature, m.p. 69° - 70° . T2I was prepared by isomerization as described for T2CH₃. It was recrystallized from alcohol at -80° , sublimed and then again recrystallized from alcohol at room temperature, m.p. 126.5° - 128.0° (lit.¹⁰⁵ 149.5° - 150.1°).

Analysis: C2I found: C = 39.2%, 39.2% H = 2.4%, 2.5%
T2I found: C = 39.2%, 39.3% H = 2.4%, 2.4%
calculated: C = 38.92% H = 2.33%

4-methoxystilbene. This compound was prepared from p-anisaldehyde and phenylacetic acid. The mixture obtained after decarboxylation was dissolved in ethyl alcohol. On cooling the solution to -80° the trans compound separated out. It was recrystallized twice from ethyl alcohol and sublimed in vacuo, m.p. 135.5° - 136.0° (lit.^{88, 90} 136° - 136.5°). The alcohol solution was evaporated and the remaining 4-methoxy-cis-stilbene distilled, b.p. 142° - 143° /2 mm (lit.^{88, 90} 141° - 142° /3 mm).

SAMENVATTING

Cis-trans isomerisaties van 1,2-digesubstitueerde ethenen kunnen worden gekatalyseerd door jodium atomen. Het jodium atoom wordt geaddeerd aan de cis verbinding (cis) waarbij een radicaal (cis-I \cdot) met enkele C-C band ontstaat. Dit radicaal roteert tot het overeenkomstige trans-I: waarna door afsplitsing van het jodium atoom de trans verbinding (trans) ontstaat.

In dit proefschrift wordt het effect van substituenten op de snelheid van de jodium-gekatalyseerde isomerisatie van cis-stilbeen beschreven. Kinetische metingen werden verricht aan 18 verschillende *symmetrisch* gesubstitueerde cis-stilbeen derivaten. De reactie werd uitgevoerd in dichtgesmolten reageerbuisjes onder uitsluiting van licht en zuurstof bij verschillende temperaturen tussen 70°C and 120°C. Tetrachloorkoolstof werd gebruikt als oplosmiddel. De reactiesnelheid bleek voor alle onderzochte verbindingen eerste orde in cis-stilbeen derivaat en evenredig met de wortel uit de jodium concentratie:

$$-d [\text{cis}] / dt = k[\text{cis}] \left[\text{I}_2 \right]^{\frac{1}{2}}$$

Dit is in overeenstemming met de onderstelling dat de reactie verloopt onder de katalyserende invloed van jodium atomen, die door thermische dissociatie uit I₂ ontstaan. De reactiesnelheidsconstanten k zijn in het algemeen bepaald met een nauwkeurigheid van 2-4% en worden uitgedrukt in eenheden l^{1/2} mole^{-1/2}h⁻¹.

Voor alle meta- en enkele para-gesubstitueerde cis-stilbenen blijkt er een lineair verband te bestaan tussen log k en de σ waarden van de substituenten (bepaald uit de dissociatieconstanten van de overeenkomstige benzoëzuren). De ρ waarde is afhankelijk van de temperatuur en varieert van -1.12 bij 120° tot -1.35 bij 70°. De negatieve waarde van ρ houdt verband met het electrofiële karakter van het jodium atoom.

Sommige para-gesubstitueerde cis-stilbenen (p,p'-dinitro-, p,p'-dicyano- en in mindere mate p,p'-dichloor-cis-stilbeen) vertonen grotere k waarden dan op grond van de Hammett relatie verwacht mag worden. Dit komt tot uitdrukking in een afwijking van de Hammett lijn

($\Delta \log k$) waarvan de grootte ongeveer evenredig bleek te zijn met de logaritme van de partial-rate-factors voor homolytische fenylering van de para positie van de overeenkomstig gesubstitueerde benzeen derivaten. Dit is een sterke aanwijzing dat deze afwijkingen veroorzaakt worden door extra resonantiestabilisatie door de para substituenten van het benzyl-type radicaal, dat ontstaat na additie van het jodium atoom aan een van de koolstof atomen van de ethyleenband. De resultaten zijn dan ook volledig in overeenstemming met het hierboven beschreven mechanisme voor cis-trans isomerisatie onder invloed van jodium atomen.

De Arrhenius activeringsparameters zijn bepaald met een nauwkeurigheid van 0.05-0.30 log A eenheden voor de frequentie factor en 0.1-0.6 kcal/mole voor de activeringsenergie. Hierdoor bleek het mogelijk om vast te stellen dat de invloeden van de substituenten op de reactiesnelheid een gevolg zijn van variaties in de activeringsenergie. Bij de gegeven nauwkeurigheidsgrenzen is de frequentie factor voor nagenoeg alle onderzochte verbindingen constant. De gemiddelde waarde van log A is 13.18, de activeringsenergie varieert van 21.3-23.6 kcal/mole. Voor meta- en para-gesubstitueerde cis-stilbenen is een algemene formule voor de reactiesnelheid op te stellen:

$$\log k = 13.18 - \frac{21.78 + 2.04\sigma - \Delta E_X^i}{2.303 RT}$$

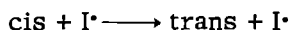
Hierin is:

σ = Hammett σ waarde

ΔE_X^i = verlaging van de activeringsenergie als gevolg van extra resonantiestabilisatie van de transition state. ΔE_X^i kan berekend worden uit de partial-rate-factor voor homolytische fenylering van de para positie van het overeenkomstige benzeen derivaat.

In alle onderzochte gevallen vertragen ortho substituenten de reactiesnelheid, kennelijk om sterische redenen. De grootte van de sterische hindering (gemeten als $\log (k_O/k_P)$, waarin k_O = reactiesnelheidsconstante van een o,o'-digesubstitueerd cis-stilbeen en k_P = reactiesnelheidsconstante van het overeenkomstige p,p'-digesubstitueerde cis-stilbeen) loopt namelijk ongeveer parallel met de van der Waals straal van de substituent.

Uit de waargenomen frequentie factor is de A factor berekend voor de reactie:



Het blijkt dat de A waarde voor dit proces ongeveer een factor 100 kleiner is dan de berekende en experimenteel gevonden waarden van A voor de aanval van jodium atomen op gesubstitueerde ethenen. Hieruit blijkt dat niet deze aanval, maar de rotatie van het intermediaire radicaal de snelheidsbepalende stap is. De waargenomen k waarde is dus gelijk aan $K_1^{\frac{1}{2}}K_1k_2$, waarin:

K_1 = dissociatieconstante van I_2 .

K_1 = evenwichtsconstante voor de reversibele additie van een jodium atoom aan de dubbele band van het cis-stilbeen derivaat.

k_2 = rotatiesnelheidsconstante van het intermediaire radicaal.

De waargenomen ρ waarde is van dezelfde orde van grootte als ρ waarden die gevonden zijn bij andere reacties van halogeen atomen. De gevonden ρ waarden worden in deze gevallen verklaard op grond van een polaire band, die ontstaat tussen het halogeen atoom en het substraat. Aangezien zo'n polaire band ook reeds gevormd is in het intermediair, mag voor de evenwichtsconstante K_1 een ρ waarde verwacht worden die ongeveer even groot is als de waargenomen ρ waarde. Dit betekent dat het inductief effect van de substituenten weinig invloed uitoefent op de rotatiesnelheidsconstante k_2 .

De gevonden afwijkingen van de Hammett lijn in het geval van para-substitueerde cis-stilbenen zijn ongeveer een factor 3 kleiner dan verwacht mag worden op grond van berekeningen van Wheland over extra resonantiestabilisatie van het benzyl radicaal door para substituenten. Deze verminderde stabilisatie kan echter goed verklaard worden op grond van de niet-vlakke structuur van het benzyl-type radicaal in de transition state voor rotatie van het intermediair cis-I.

In hoofdstuk V wordt speciale aandacht besteed aan de jodium-gedirecteerde isomerisatie van para-methoxy-cis-stilbenen (mono- en digesubstitueerd). Deze verbindingen bleken reeds bij kamertemperatuur met jodium te isomeriseren, blijkbaar via een ander mechanisme. Uit kinetische metingen bij temperaturen van 5° - 40° is gevonden dat de activeringsenergie voor isomerisatie via dit mechanisme ongeveer -2 kcal/mole bedraagt. De reactiesnelheid is eerste orde in cis-stilbeen derivaat en de orde in jodium is ongeveer $3\frac{1}{2}$. De orde in jodium daalt als de reactie wordt uitgevoerd in een meer polair oplosmiddel (ijsazijn). De reactiesnelheid wordt niet beïnvloed door de aanwezigheid van zuurstof. Er is een vergelijking gemaakt met andere processen die eveneens van een hoge orde met betrekking tot halogeen zijn in apolaire oplosmiddelen, t.w. additie aan olefinen en aromatische sub-

stitutie. Mede op grond hiervan is een mechanisme voorgesteld waarbij in de eerste stap een 1 : 1 molecuulair complex van jodium en cis-stilbeen derivaat wordt gevormd. Dit complex wordt onder invloed van 2 of 3 extra jodium moleculen omgezet in het carbonium ion cis-I[⊕] en I[⊖]. Het jodide ion wordt gebonden in de vorm van I₅[⊖] en I₇[⊖] ionen. Het carbonium ion, met enkele C-C band, roteert tot het overeenkomstige trans-I[⊕] waarna door afsplitsing van I[⊕] het trans-stilbeen derivaat resulteert.

De syntheses van de gebruikte verbindingen worden in het laatste hoofdstuk beschreven. De cis-stilbeen derivaten zijn gemaakt door Perkin condensatie van gesubstitueerde benzaldehyden en fenylazijnzuren. Na decarboxylatie van het ontstane α-fenyl-trans-kaneelzuur derivaat werd het overblijvende mengsel van cis- en trans-stilbeen derivaat door kolomchromatografie gezuiverd. De cis en trans verbindingen werden vervolgens door gefractioneerde kristallisatie gescheiden.

REFERENCES

1. E.S.Gould, "Mechanism and Structure in Organic Chemistry", Holt, Rinehart and Winston, Inc. New York (1962), a) p. 736, 737 b) p. 514-527
2. C.Walling, "Free Radicals in Solution", John Wiley and Sons, Inc. New York (1957), a) p. 49 b) p. 241 c) Chapter 8 d) p. 138, 139
3. M.Ballester and J.Rosa, *Tetrahedron* 9, 156 (1960)
4. H.Steinmetz and R.M. Noyes, *J. Am. Chem. Soc.* 74, 4141 (1952)
5. R.M.Noyes, R.G.Dickinson and V.Schomaker, *J. Am. Chem. Soc.* 67, 1319 (1945)
6. R.E.Wood and R.G. Dickinson, *J. Am. Chem. Soc.* 61, 3259 (1939)
7. R.G.Dickinson, R.F.Wallis and R.E.Wood, *J. Am. Chem. Soc.* 71, 1238 (1949)
8. A.Berthoud and C.Urech, *J. Chim. Phys.* 27, 291 (1930)
9. R.G.Dickinson and H.Lotzkar, *J. Am. Chem. Soc.* 59, 472 (1937)
10. E.A.R. Visscher, Thesis, Leiden (1963)
11. E.A.R. Visscher and E.C.Kooyman, *J. Catalysis* 2, 421 (1963)
12. S.Yamashita, *Bull. Chem. Soc. Jap.* 34, 487 (1961)
13. S.Yamashita, *Bull. Chem. Soc. Jap.* 34, 972 (1961)
14. G.Cauzzo, U. Mazzucato and G.Aloisi, *Gazz. Chim. Ital.* 96, 721 (1966)
15. S.W.Benson, K.W.Egger and D.M.Golden, *J. Am. Chem. Soc.* 87, 468 (1965)
16. K.W.Egger and S.W.Benson, *J. Am. Chem. Soc.* 87, 3314 (1965)
17. S.Yamashita, *Bull. Chem. Soc. Jap.* 34, 842 (1961)
18. M.S. Newman, *J. Am. Chem. Soc.* 72, 4783 (1950)
19. R.Branston Williams, *J. Am. Chem. Soc.* 64, 1395 (1942)
20. W.J.Muizebelt and R.J.F.Nivard, *Chem. Comm.* 148 (1965)
21. E.A.Guggenheim and J.E.Prue, "Physico-chemical Calculations", North-Holland Publishing Company, Amsterdam (1955) p.444
22. J.Hine, "Physical Organic Chemistry", Mc Graw-Hill Book Company, Inc. New York (1962) p.87
23. H.H.Jaffé, *Chem. Reviews* 53, 191 (1953)

24. M.S.Newman, "Steric Effects in Organic Chemistry", John Wiley and Sons, Inc. New York (1956) a) R.W.Taft, Chapter 13 b) p.552
25. R.W.Taft, M.S.Newman and F.H.Verhoek, *J. Am. Chem. Soc.* 72, 4511 (1950)
26. R.W.Taft, *J. Am. Chem. Soc.* 74, 3120 (1952)
27. L.F.Meadows and R.M.Noyes, *J. Am. Chem. Soc.* 82, 1872 (1960)
28. H.Rosman and R.M.Noyes, *J. Am. Chem. Soc.* 80, 2410 (1958)
29. A.A.Frost and R.G.Pearson, "Kinetics and Mechanism", John Wiley and Sons, Inc. New York (1961) a) p. 110, 111 b) p.94
30. K.L.Müller and H.J.Schumacher, *Z. physik. Chem.* B39, 352 (1938)
31. K.L.Müller and H.J.Schumacher, *Z. physik. Chem.* B42, 327 (1939)
32. G.A.Russell, *J. Org. Chem.* 23, 1407 (1958)
33. C.Walling and B.Miller, *J. Am. Chem. Soc.* 79, 4181 (1957)
34. R.van Helden and E.C.Kooyman, *Rec. Trav. Chim.* 73, 269 (1954)
35. G.A.Russell and R.C.Williamson, *J. Am. Chem. Soc.* 86, 2357 (1964)
36. H.C.Brown and Y.Okamoto, *J. Am. Chem. Soc.* 80, 4979 (1958)
37. E.C.Kooyman, R.van Helden and A.F.Bickel, *Koninkl. Ned. Akad. Wetensch. Proc.* B56, 75 (1953)
38. C.Walling, A.L.Rieger and D.D.Tanner, *J. Am. Chem. Soc.* 85, 3129 (1963)
39. R.E.Pearson and J.C.Martin, *J. Am. Chem. Soc.* 85, 3142 (1963)
40. E.S. Huyser, *J. Am. Chem. Soc.* 82, 394 (1960)
41. W.A. Pryor, "Free Radicals", Mc Graw-Hill Book Company, Inc. New York (1966) p. 170-176
42. W.E.Hanford and R.Adams, *J. Am. Chem. Soc.* 57, 1592 (1935)
43. I.J. Gardner and R.M.Noyes, *J. Am. Chem. Soc.* 83, 2409 (1961)
44. G.H.Williams, "Homolytic Aromatic Substitution", Pergamon Press, Oxford (1960) p.73
45. R.Itô, T.Migita, N.Morikawa and O.Simamura, *Tetrahedron* 21, 955 (1965)
46. C.A.Coulson and E.Theal Stewart, Chapter I, p. 137 in: S.Patai, "The Chemistry of Alkenes", Interscience Publishers, London (1964)
47. M.Szwarc, *Chem. Reviews*, 47, 75 (1950)
48. J.A.Kerr, *Chem. Reviews*, 66, 465 (1966)
49. S.J.Price, *Can. J. Chem.* 40, 1310 (1962)
50. G.L.Esteban, J.A.Kerr and A.F.Trotman-Dickenson, *J. Chem. Soc.* 3873 (1963)
51. R.Walsh, D.M.Golden and S.W.Benson, *J. Am. Chem. Soc.* 88, 650 (1966)
52. G.W.Wheland, "Resonance in Organic Chemistry", Wiley and Sons,

- Inc. New York (1955) a) p. 384 b) p. 80
53. I.Fisher-Hjalmars, *Tetrahedron* 19, 1805 (1963)
 54. F.J.Adrian, *J.Chem. Phys.* 28, 608 (1958)
 55. G.S.Hammond, *J.Am. Chem. Soc.* 77, 334 (1955)
 56. S.Winstein and N.J. Holness, *J.Am. Chem. Soc.* 77, 5562 (1955)
 57. L.Bruner, *Z.physik. Chem.* 41, 513 (1902)
 58. C.C.Price, *J.Am. Chem. Soc.* 58, 2101 (1936)
 59. C.C.Price and C.E.Arntzen, *J. Am. Chem. Soc.* 60, 2835 (1938)
 60. C.C.Price, *Chem. Reviews* 29, 37 (1941)
 61. P.W.Robertson, J.E.Allan, K.N.Haldane and M.G.Simmers, *J.Chem. Soc.* 933 (1949)
 62. Teiji Tsuruta, Ken-ichi Sasaki and Junji Furikawa, *J. Am. Chem. Soc.* 76, 994 (1954)
 63. J.H.Blake and R.M.Keefer, *J.Am. Chem. Soc.* 77, 3707 (1955)
 64. H.D.C.Waters, A.R.Caverhill and P.W.Robertson, *J.Chem. Soc.* 1168 (1947)
 65. P.B.D.de la Mare, R.A.Scott and P.W.Robertson, *J.Chem. Soc.* 509 (1945)
 66. L.J.Lambourne and P.W.Robertson, *J.Chem. Soc.* 1167 (1947)
 67. A.H.Neyens, *Bull. Soc. Chim. France* 719 (1961)
 68. L.J.Andrews and R.M.Keefer, *J.Am. Chem. Soc.* 79, 1412 (1957)
 69. L.J.Andrews and R.M.Keefer, "Molecular Complexes in Organic Chemistry" Holden-Day, Inc. San Francisco (1964) p. 154-156
 70. A.H.Neyens and J.C.Jungers, *Bull. Soc. Chim. France* 1481 (1959)
 71. R.M.Keefer, A.Ottenberg and L.J.Andrews, *J. Am. Chem. Soc.* 78, 255 (1956)
 72. R.M.Keefer and L.J.Andrews, *J.Am. Chem. Soc.* 78, 5623 (1956)
 73. R.M.Keefer and L.J.Andrews, *J.Am. Chem. Soc.* 78, 3637 (1956)
 74. L.J.Andrews and R.M.Keefer, *J.Am. Chem. Soc.* 78, 4549 (1956)
 75. M.Davies and E.Gwynne, *J.Am. Chem. Soc.* 74, 2748 (1952)
 76. A.Goldman and R.M.Noyes, *J.Am. Chem. Soc.* 79, 5370 (1957)
 77. W.H.Laarhoven and R.J.F.Nivard, *Rec. Trav. Chim.* 84, 1478 (1965)
 78. L.J.Andrews and R.M.Keefer, *J.Am. Chem. Soc.* 74, 4500 (1952)
 79. G.A.Latrémouille and A.M.Eastham, *Can. J. Chem.* 45, 11 (1967)
 80. M.Bakunin and D.Peccerillo, *Gazz. Chim. Ital.* 65, 1145 (1935)
 81. *Organic Syntheses* 33, 70, 88 (1953)
 82. R.E. Buckles and J.A.Cooper, *J.Org. Chem.* 30, 1588 (1965)
 83. R.Ketcham and D.Jambotkar, *J.Org. Chem.* 28, 1034 (1963)
 84. O.H.Wheeler and H.N.Battle de Pabon, *J.Org. Chem.* 30, 1473 (1965)
 85. T.W.J.Taylor and C.E.J.Crawford, *J.Chem.Soc.* 1130 (1934)
 86. L.F.Fieser, *J. Chem. Educ.* 31, 291 (1954)

87. R.E.Buckles, M.P.Bellis and W.D.Coder, *J. Am. Chem. Soc.* 73, 4972 (1951)
88. G.A.R. Kon and R.G.W.Spickett, *J. Chem. Soc.* 2724 (1949)
89. F.D.Greene, W.Adam and J.E.Cantrill, *J. Am. Chem. Soc.* 83, 3461 (1961)
90. G.Riezebos, Thesis, Leiden (1959)
91. W.J.E.Voet, Thesis, Leiden (1964)
92. W.G.B.Huysmans, Thesis, Leiden (1964)
93. J.B.Shoesmith and J.F. Mc Gechen, *J. Chem. Soc.* 2231 (1930)
94. A.I.Vogel "Practical Organic Chemistry", Longmans, Green and Co., London (1957) p.700
95. Th.Posner, *J. Prakt. Chem.* 82, 431 (1910)
96. J.Arotsky, R.Butler and A.C.Darby, *Chem. Comm.* 650 (1966)
97. L.Friedman and H.Schechter, *J. Org. Chem.* 25, 877 (1960)
98. R.Jaeger and R.Robinson, *J. Chem. Soc.* 744 (1941)
99. W.S. Rapson and R.G.Shuttleworth, *J. Chem. Soc.* 487 (1941)
100. J.G.Watkinson, W.Watson and B.L.Yates, *J. Chem. Soc.* 5437 (1963)
101. W.Tadros, L.Ekladius and A.Badie Sakla, *J. Chem. Soc.* 2351 (1954)
102. L.Aronstein and A.S.van Nierop, *Rec. Trav. Chim.* 21, 448 (1902)
103. J.Coops, G.J.Hoijtink, T.J.E.Kramer and A.C.Faber, *Rec. Trav. Chim.* 72, 765 (1953)
104. F.Bergmann and H.Japhé, *J. Chem. Soc.* 1450 (1947)
105. J.A.Stanfield and L.B.Reynolds, *J. Am. Chem. Soc.* 74, 2878 (1952)
106. S.M.Spatz, *J. Org. Chem.* 26, 4158 (1961)
107. S.Bance, H.J.Barber and A.M.Woolman, *J. Chem. Soc.* 1 (1943)
108. P.l'Ecuyer and F.Turcotte, *Can. J. Res.* 25B, 575 (1947)

STELLINGEN

1

De snelle ontleding van p-methoxybenzyljodide onder invloed van jodium verloopt via een ionenmechanisme.

I.J. Gardner en R.M. Noyes, *J. Am. Chem. Soc.* **83**, 2409 (1961)

2

De partial-rate-factors voor homolytische fenylering van de para positie van benzeen derivaten geven ook een relatieve maat voor de extra resonantiestabilisatie van de overeenkomstig gesubstitueerde benzyl radicalen.

Dit proefschrift

3

De door Hodgkins en Dennis Megarity gemeten verschuivingen in het U.V. absorptie maximum van gesubstitueerde benzyl radicalen worden door Kennedy en Ingold ten onrechte geïnterpreteerd als een maat voor de extra resonantiestabilisatie van het benzyl radicaal door de substituent.

J.E. Hodgkins en E. Dennis Megarity, *J. Am. Chem. Soc.* **87**, 5322 (1965)

B.R. Kennedy en K.U. Ingold, *Can. J. Chem.* **44**, 2381 (1966)

4

Bijde reactie tussen olefinen en positieve halogeen ionen ontstaan zowel cyclische halogeenonium ionen als asymmetrische 'open' carbonium ionen.

K. Yates en W.V. Wright, *Can. J. Chem.* **45**, 167 (1967)

Dit proefschrift

5

Ten onrechte wordt in leerboeken over fysische chemie gesteld dat reacties van een hogere orde dan drie niet voorkomen.

A.J. Verbrugh en W.L. Ghijsen, 'Elementaire Inleiding tot de

Physische Scheikunde', deel II, p.346 (1955)
S. Glasstone en D. Lewis, 'Elements of Physical Chemistry',
p.602 (1964)
A.K. Barnard en A.L. Mansell, 'Fundamentals of Physical
Chemistry', p.191 (1966)

6

De verklaring die Brackman en Plesch geven voor het niet-constant
zijn van het smeltpunt van cis-stilbeen is onwaarschijnlijk.
D.S. Brackman en P.H. Plesch, J.Chem.Soc. 2188 (1952)

7

Bij de bepaling van het pH optimum van allantoinase uit sojabonen
hebben Franke et al. geen rekening gehouden met de remmende wer-
king van fosfaatbuffers op de enzymatische activiteit.
W. Franke et al., Enzymologia 29, 251 (1965)
G.D. Vogels, F. Trijbels en A. Uffink, Biochimica et Biophysica
Acta 122, 482 (1966)

8

Bijde door Hagedorn en Lichtel beschreven synthese van tetrakis-[N-
methylanilino] -ethyleen uit N-methylaniline en ethylorthoformiaat
wordt het product pas gevormd tijdens het concentreren van het reac-
tiemengsel.
I. Hagedorn en K.E. Lichtel, Chem.Berichte 99, 526 (1966)

9

De conclusies die Müller et al. trekken uit de gemeten ^{13}C en ^{17}O
hyperfijnsplitsingen in het E.S.R.spectrum van het 2,4,6-tri-tert.-
butyl-fenoxyradicaal zijn weinig zinvol.
E. Müller et al., Angewandte Chemie 78, 103 (1966)

10

Bij het Twentse Midwinterhoorn blazen verdient de natte gekuipde
hoorn de voorkeur boven de droge gelijkde hoorn.

11

Bij de bestudering van de nucleofiele aanval van *Aminus improbabilis*
op het 'lesser web-footed' keteen moet meer aandacht besteed worden
aan het elektronenverlies van het zuurstof atoom.
R.H.B. Galt en S.D. Mills, Chemistry in Britain 1, 230 (1965)

