Translated from *Uspekhi Khimii*, **43**, 1771-1793 (1974) U.D.C. 547.212; 547.311.2; 547.324

Diene Synthesis with 2-Pyrones and 2-Pyridones

N.P.Shusherina

The principal aspects of Diels-Alder synthesis with six membered heterocyclic dienes (2-pyrones and 2-pyridones) as well as the latest data on the *endo-exo* selectivity of this reaction are considered.
The bibliography includes 121 references.

CONTENTS

I. Introduction 851
II. Monoadducts of 2-pyrones {derivatives of 8-oxabicyclo[2,2,2]oct-4-en-7-one} 851
III. Diene synthesis with 2-pyrones accompanied by the elimination or rupture of the lactone bridge in the monoadducts 854
IV. Diene synthesis with 2-pyridones 856
V. The stereochemistry of diene synthesis with 2-pyrones and 2-pyridones 857

I. INTRODUCTION

The diene synthesis reaction discovered more than 40 years ago constitutes at present a universal method for the preparation of a wide variety of cyclic systems. The employment in the Diels–Alder reaction of heterocyclic compounds with a conjugated system of C=C double bonds, among which furan, oxazole, 2-pyrone, and 2-pyridone derivatives react via the normal (4+2)-cycloaddition mechanism (with yields of adducts on a preparative scale), is of particular interest.

The practical and theoretical problems of diene synthesis with furans and oxazoles have been discussed in a number of papers and monographs [1,2], while the behaviour of 2-pyrones and 2-pyridones in this reaction has been scarcely considered in the review literature [3].

The studies published in the last decade, in which the interaction of 2-pyrones and dienophiles was used to obtain barrelene, colchicine analogues, compounds of the cyclohexatriene series and various aromatic and bridged polycyclic compounds which are difficult to obtain otherwise, demonstrate the wide synthetic possibilities of the use of 2-pyrones in the Diels–Alder reaction.

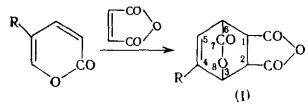
The reactions of 2-pyridones with dienophiles lead to the formation of bicyclic systems with an endazocarbonyl bridge. Extremely interesting theoretical data have been obtained in a study of the stereochemistry of diene synthesis with 2-pyrones and 2-pyridones.

The present review gives a systematic account of the literature on diene synthesis with the above six-membered heterocycles.

II. MONOADDUCTS OF 2-PYRONES {DERIVATIVES OF 8-OXABICYCLO[2,2,2]OCT-4-EN-7-ONE}

1. Synthesis

The ability of 2-pyrones to eneter into diene synthesis was first observed by Diels and Alder in the reactions of 2-pyrone and 5-methoxycarbonyl-2-pyrone (methyl coumalate) with maleic anhydride. The authors [4] showed that the monoadducts (I) {derivatives of 8-oxabicyclo-[2,2,2]oct-4-en-7-one} are formed on refluxing equimolar amounts of the initial reactant in toluene at 110°C:



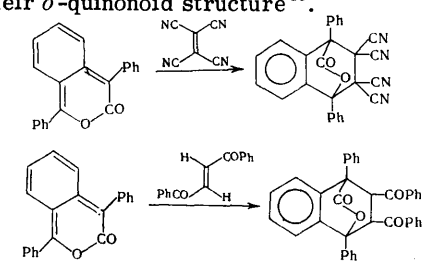
(R = H, COOMe) (I)

However, owing to their thermal instability the monoadducts of 2-pyrones are difficult to obtain. They can be synthesised only from 2-pyrones and dienophiles which enter into diene synthesis at temperatures below the decomposition temperatures of the monoadducts. It has been established that alkyl and particularly aryl groups in the 6-position of the initial 2-pyrone reduce the stability and hinder (frequently altogether preclude) the formation of the monoadducts [5,6] (cf. the part of subsection 2 dealing with thermolysis).

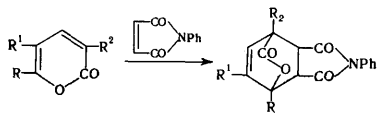
According to Alder's rule [1], electron-accepting substituents in the molecules of the initial pyrone reduce the yield of monoadducts (see Table).

An idea concerning the relative reactivities of dienophiles in reactions with 2-pyrones can be gained from a study [14] where it was shown that the yield of the monoadducts of the *o*-quinonoid 2-benzopyrone fell and the duration of the reaction increased in the series of the following dienophiles: *N*-phenylmaleimide (yield up to 85%, 25 min), dimethyl maleate (32%, 1.5 h), dimethyl fumarate (12%, 3 h).

The successive employment of tetracyanoethylene and benzoylethylene as dienophiles in reactions with 6-methyl- and 3,6-diphenyl-4,5-benzo-2-pyrones has been described. The unusual ease of this reaction is related to the enhanced diene reactivity of the above pyrones in consequence of their *o*-quinonoid structure [15].

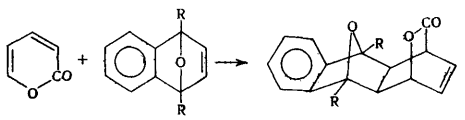


Among the dienophiles enumerated above, only *N*-phenylmaleimide [16] has been studied in reactions with the usual 2-pyrones, monoadducts being formed at 110°C:



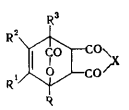
(R = R¹ = R² = H; R = R¹ = Me; R₂ = H; R¹ = R = H; R² = Br)

The ease of the reaction of 1,4-endoxy-1,4-dihydronaphthalene with 2-pyrone is due to the strain of the double bond in the dienophile [17]. The authors attributed the *exo*-configuration to the adduct without proof [17].



(R = H, Me)

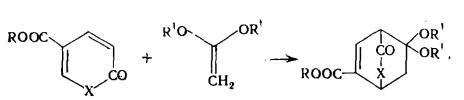
The monoadducts of 2-pyrones with maleic anhydride and *N*-phenylmaleimide.



No.	Initial 2-pyrone	R	R¹	R²	R³	X	Yield, %	Reaction conds. temp., °C	Reaction conds. time, h	Refs.
1	2-pyrone	H	H	H	H	O	50	110	10	4,7
2	ditto	H	H	H	H	NPh	80	110	1	16
3	3-bromo-2-pyrone	H	H	H	Br	O	20	110*	19	6
4	ditto	H	H	H	Br	NPh	25	110	1.5	16
5	5-methyl-2-pyrone	H	Me	H	H	O	—	110	1	9
6	5-isopropyl-2-pyrone	H	Et	H	H	O	—	110	12	10
7	5-methoxycarbonyl-2-pyrone	H	COOMe	H	H	O	30	110	3	4
8	5,6-dimethyl-2-pyrone	Me	Me	H	H	O	55	80	1	5
9	ditto	Me	Me	H	H	NPh	48	80	3	16
10	5-cyclohexyl-2-pyrone	H	C_6H_{11}	H	H	O	—	110	14	8
11	5,6-tetramethylene-2-pyrone	$(CH_2)_4$	$(CH_2)_4$	H	H	O	8—10	80*	10*	5
12	6-acetoxymethyl-5-methyl-2-pyrone	CH_2OCOMe	Me	H	H	O	72	110	3	13
13	ditto	CH_2OCOMe	Me	H	H	NPh	60	110	3	16
14	6-bromomethyl-5-methyl-2-pyrone	CH_2Br	Me	H	H	O	40	110	2	5
15	6-methyl-5-phenyl-2-pyrone	Me	Ph	H	H	O	13	110*	1*	6
16	6-methyl-4,5-benzo-2-pyrone	Me	R¹+R²-ato-benzene		H	NPh	81	140	1.5	14
17	3,6-diphenyl-4,5-benzo-2-pyrone	Ph	R¹+R²-ato-benzene		Ph	NPh	—	20	264	15

*An increase of the reaction temperature and of the duration of heating lead to a sharp lowering of the yields of the monoadducts owing to their conversion into bisanhydrides and bisimides (see Section III, 1). [5,6,11,12]

Keten diacetals, whose interaction with 5-alkoxycarbonyl-2-pyrones and their sulphur analogues gave monoadducts with yields on a preparative scale, proved to be extremely reactive dienophiles [18]:

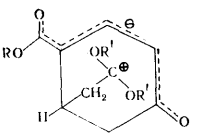


(X = O, S; R and R¹ = Me, Et)

This reaction involving 2-pyrones illustrates the possibilities of diene synthesis with "inverse electron demand", since here the electron donor is a dienophile (keten diacetal) whose double bond exhibits enhanced nucleophilic properties and the acceptor is the diene system of the 2-pyrone.

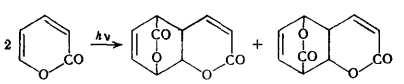
The present authors achieved the interaction with keten acetals via the inverse mechanism only for 2-pyrones with electron-accepting groups: the unsubstituted 2-pyrone does not enter into this reaction [18].

It might have been expected that two structural isomers would be obtained in the reaction of asymmetric diene synthesis addends—5-alkoxycarbonyl-2-pyrones and keten diacetals. However, in the instances investigated only the isomer with the *para*-disposition of the substituent was obtained, which the authors explain by the greater stabilisation of the transition state (A) of this isomer compared with the possible transition state for the *meta*-isomer [18].



(A)

On the other hand, the dimerisation of 2-pyrone (on ultraviolet irradiation) via a process of the diene synthesis type, in which the asymmetric 2-pyrone molecule behaves both as the diene and the dienophile, leads to a mixture of both possible structural isomers [19]:

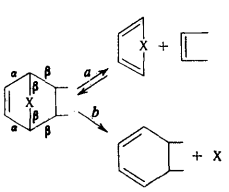


2. The Properties of Monoadducts

Thermolysis. A characteristic property of bridged 1,4-cycloadducts is their ability to dissociate on thermolysis the bond in the β-position relative to the double bond and to undergo retrodiene decomposition (reversible reaction *a*) and retrodiene elimination of the bridge (irreversible reaction *b*, see Scheme). Both modes of cleavage of the cycloadducts predicted by the Schmidt rule [20,21] are associated with a weakening of the above σ-bonds in ethylene compounds owing to the additional stabilisation of the intermediate species arising in the decomposition of these bonds, as happened, for example, with allyl cations.

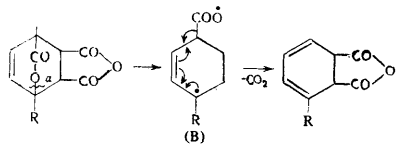
Among the known bicyclic adducts with various *endo*-bridges [X = CH_2, O, CO, $(CH)_2$], [1] the monoadducts of 2-pyrones (X = CO_2, see Scheme) are the least stable on heating, whereupon CO_2 is usually eliminated (retrodiene elimination of the bridge, reaction *b*). Certain adducts decompose at a temperature as low as 60°C and only in rare instances (in the absence of substituents at the head of the bridge) can they withstand heating above 130—140°C.

Scheme



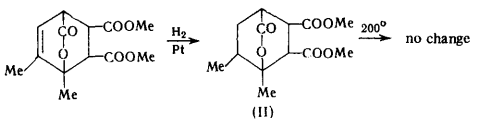
X = CH_2, $(CH_2)_2$, O, CO, CO_2

On the basis of the primary isotope effects of carbon and oxygen found for the monoadducts of 2-pyrone with maleic anhydride, Goldstein and Thayer [7] concluded that the elimination of CO_2 is a two-stage process, which begins with the dissociation of bond *a*. The resulting biradical (B) is converted further into the more stable cyclohexadiene system:

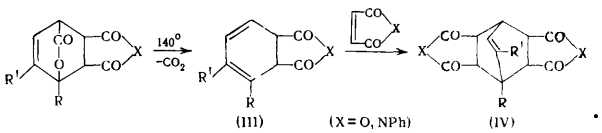


This hypothesis concerning the course of the thermolysis explains the instability of monoadducts with substituents at the bridgehead (R = alkyl or aryl) by the stabilisation of the biradical (B) owing to the $+I$ and $+M$ effects of the substituents. On the other hand, even weak electron-accepting groups in this position (for example CH_2Br and CH_2OCOMe, see Nos. 12–14 in Table) appreciably increase the stability of the monoadducts.

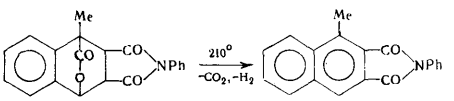
The lability of the bridge due to the influence of the double bond disappears in the hydrogenated adducts—8-oxabicyclo[2,2,2]octan-7-ones (II), which withstand heating above 200°C: [22]



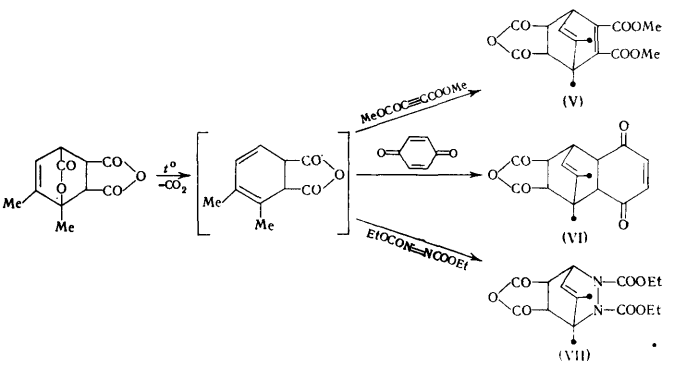
The products of the elimination of CO_2 from the adducts of 2-pyrones with maleic anhydride and *N*-phenylmaleimide, the corresponding derivatives of cyclohexadienecarboxylic acids (III), were characterised as bisanhydrides [5] and bisimides [6] (IV):



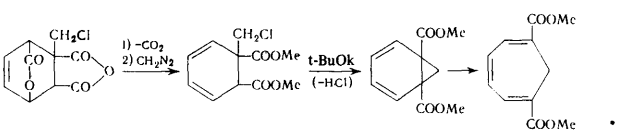
On heating above 200°C in nitrobenzene, the adducts are aromatised [14]:



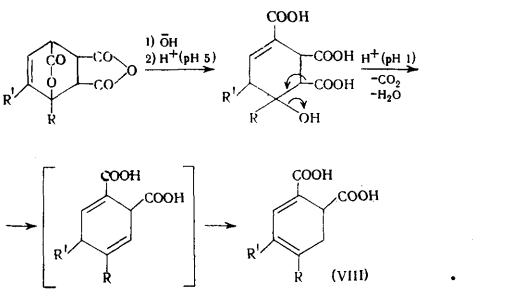
The thermolysis of the adducts with maleic anhydride in the presence of other dienophiles (acetylenedicarboxylic acid ester, benzoquinone, azodicarboxylic acid ester) made it possible to obtain mixed adducts with two dienophiles of different chemical types—compounds of the bicyclo[2,2,2]-octadiene (V) and bicyclo[2,2,2]octene (VI) series and a heterocyclic analogue (VII) of the latter with two nitrogen atoms in the ring [23]:



The cyclohexadiene systems formed on thermolysis of the monoadducts have been used also for other synthetic purposes, for example, for the formation of the cycloheptatriene ring [24,25]:

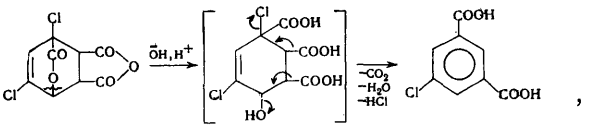


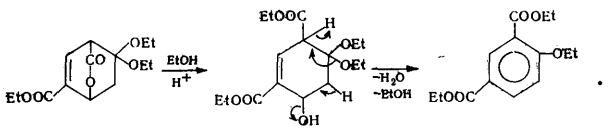
The opening of the lactone bridge under the influence of nucleophilic agents takes place with different degrees of difficulty depending on the substitution of the 6-position. Levina, Shusherina and coworkers, established that the hydrolysis of the bridge in the adducts of 5,6-disubstituted 2-pyrones with maleic anhydride (by treatment with aqueous solutions of alkali at 20–60°C) leads to the formation of the corresponding hydroxytricarboxylic acids which undergoes synchronous dehydration and decarboxylation at pH 1 (at 20°C), being converted into cyclohexadienedicarboxylic acids (VIII); the latter are readily aromatised on heating [13].



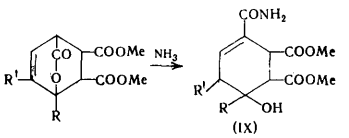
An example of the direct conversion of the adducts of 2-pyrones into aromatic compounds under the influence of nucleophilic agents is provided by the synthesis of 5-chloroisophthalic acid (in the alkaline hydrolysis of the adduct of 3,5-dichloro-2-pyrone with maleic anhydride [26])

and diethyl 4-ethoxyisophthalate (in the acid ethanolysis of the adduct of 5-ethoxycarbonyl-2-pyrone with the diethyl acetal of keten [18]):





In the ammonolysis of the esters obtained from the adducts of 2-pyrones with maleic anhydride it was possible to isolate the primary bridge-opening products—the amides of the corresponding hydroxyacids (IX): [27]

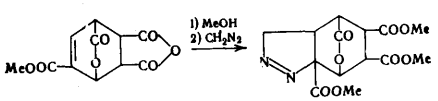


(IX)

It has been shown by ^{1}H NMR that the hydrolysis and ammonolysis of the monoadducts are accompanied by the migration of the double bond to the position conjugated with the carboxy- or carboxamido-groups arising in these processes [13,27].

Electrophilic addition to the double bond of the monoadducts of 2-pyrones (halogenation and oxidation) has been investigated to establish their configuration (see Section V).

1,3-Cycloaddition to the double bond of 8-oxabicyclo[2,2,2]oct-4-en-7-ones has been studied for adducts of alkyl coumalates with keten acetal [18], maleic anhydride, and *N*-phenylmaleimide [28]. The activated (by conjugation with the carboxy-group) double bonds of these compounds combine very readily with diazomethane, forming tricyclic Δ′-pyrazolines (X) with an endoxycarbonyl bridge:



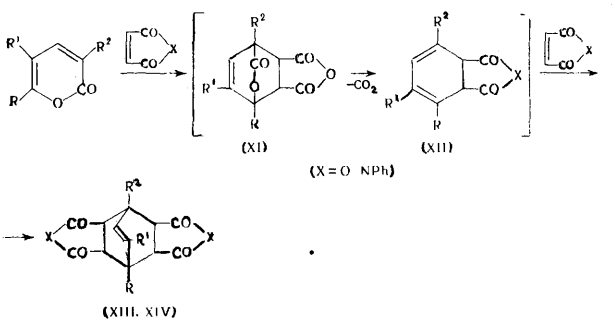
(X)

Similarly the adducts of alkyl coumalates with keten acetal combine with phenyl azide via the double bond [18]. However, the adducts of 2-pyrones with maleic anhydride without electron-accepting substituents at the double bond react neither with diazomethane nor with phenyl azide [28], which indicates an extremely weak strain of the double bond in 8-oxabicyclo[2,2,2]oct-4-en-7-ones whose geometry is close to that of the unstrained bicyclo[2,2,2]oct-4-enes [29].

III. DIENE SYNTHESIS WITH 2-PYRONES ACCOMPANIED BY THE ELIMINATION OR RUPTURE OF THE LACTONE IN THE MONOADDUCTS

1. Double Diene Synthesis (the Formation of Bridged Polycyclic Systems)

As a rule the interaction of 2-pyrones with dienophiles above 140°C is accompanied by the elimination of CO_2 from the monoadducts (XI) and the addition of a second dienophile molecule to the cyclohexadiene systems (XII) formed [3]†. Therefore, the reactions of 2-pyrones with maleic anhydride [4,11,12] and *N*-phenylmaleimide [16] under these conditions lead immediately to the bisanhydrides (XIII) and bisimides (XIV) respectively. The mechanism of the formation of (XIII) and (XIV) was confirmed by synthesis [the interaction of authentic *cis*-1,2-dihydrophthalic anhydride (XII, X = O) with maleic anhydride [4]] and also by the isolation of cyclohexadiene compounds (XII) in the thermolysis of the monoadducts (XI) (see above [16,17]):



(XI) (XII) (X = O, NPh)

(XIII, XIV)

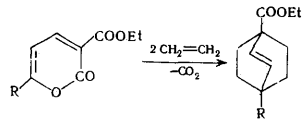
While the monoadducts can be obtained only from a few 2-pyrones substituted in specific positions (cf. the reaction described above), the products of double diene synthesis—bisanhydrides (XIII) and bisimides (XIV)—have been obtained from pyrones with different structures and a wide range of dienophiles. Thus bisanhydrides (XIII) are obtained in high yields from 6-aryl-2-pyrones [31], 5,6-dialkyl-2-pyrones [11,12], coumalic acid esters [32], tetrachloro-2-pyrones [26], 3-benzyl-2-pyrones [33], and other 2-pyrones [34-36] by the reaction with maleic anhydrides at 140°C.

High-melting crystalline bisanhydrides or the tetracarboxylic acid esters obtained from them are derivatives of 2-pyrones and are used to demonstrate the presence of the α-pyrone ring in the molecule [11,32-33,37].

Bisanhydrides are readily formed from 2-pyrones with weak electron-accepting groups (Br, CH_2Cl, CH_2OCOMe, NHCOMe) in the 3-position [38,39] (at 140°C) and also in the 3- and 5-positions [34,35]. However, 3-nitro- and 3-sulpho-2-pyrones [40,41] as well as 3,4,5-trichloro-6-phenyl-2-pyrone [26] do not react with maleic anhydride. A number of other dienophiles (benzoquinones and anthraquinones [32], acrylonitrile [42], phenyltriazoline-3-dione [43], and ethyl vinyl ether [18]) react with 2-pyrones only via the double diene synthesis mechanism (the elimination of CO_2 from

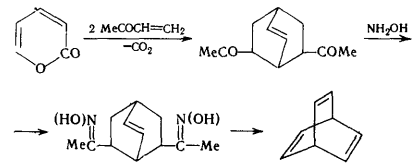
† Double diene synthesis occurs also with other cyclic dienes whose adducts readily eliminate the *endo*-bridge (for example with cyclone adducts [30]).

the monoadduct and the addition of a second dienophile molecule). 2-Pyrones react via this mechanism with ethylene, which is a weak dienophile (120–165°C, 1000 atm):[44]

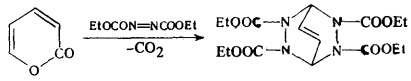


(R = Me, Et)

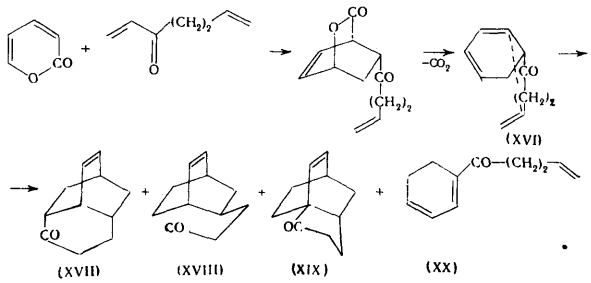
A classical example of the employment of double diene synthesis with pyrones is provided by the synthesis of barrelene {bicyclo[2,2,2]octa-1,4,7-triene} by the reaction of the unsubstituted 2-pyrone with methyl vinyl ketone[45,46] according to the following Scheme:



The employment of azodicarboxylic acid ester in diene synthesis with 2-pyrone made it possible to obtain a new heterocyclic system of the tetrazabicyclo[2,2,2]oct-2-ene series (XV):[47]

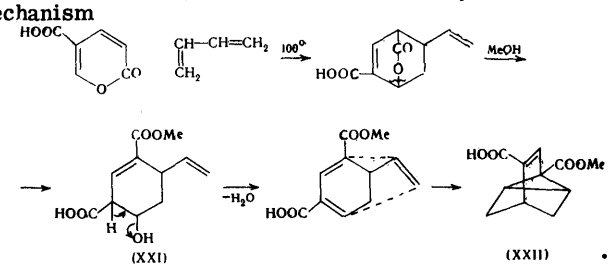


The recently investigated interaction of 2-pyrones with certain diene systems, which provide in succession both double bonds as dienophilic moieties, constitutes an unusual variant of double diene synthesis. Cyclohepta-1,6-diene-2-one reacts in this way with 2-pyrones. After the elimination of a CO_2 molecule from the monoadduct, the intramolecular interaction of the cyclohexadiene system of compound (XVI) with the double bond of the dienone fragment leads to the formation of a mixture of three isomeric tricyclic ketones (XVII), (XVIII), and (XIX) and the cyclohexadiene ketone (XX):[48]



(XVII) (XVIII) (XIX) (XX)

The double Diels–Alder reaction between coumalic acid and butadiene[49] served as a convenient method for the synthesis of tricyclene derivatives (XXII). When the process is carried out under pressure in methanol solution, the bridge in the monoadduct undergoes methanolysis, which is followed by intramolecular diene synthesis via the mechanism

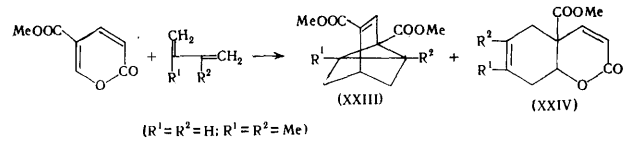


(XXI) (XXII)

Thus, in contrast to the examples described above, in this case the cyclohexadiene system does not arise in consequence of the elimination of the bridge but as a result of its rupture under the influence of methanol with subsequent dehydration of the hydroxyacid (XXI).

The interaction of coumalic acid with isoprene and dimethylbutadiene takes place similarly[49]. The unusual behaviour of typical dienes functioning as dienophiles in the reaction with coumalic acid can be explained by the occurrence of diene synthesis with "inverse electron demand" (cf. Section II, 1).

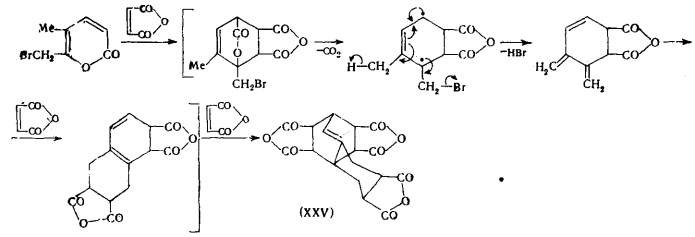
Methyl coumalate reacts with dienes in two ways—with formation of substituted tricyclo-octenes (XXIII) (as described above) and lactones (XXIV), which are obtained when methyl coumalate plays the role of the dienophile[50]:



(XXIII) (XXIV)

($R^1 = R^2 = H$; $R^1 = R^2 = Me$)

The only example of triple diene synthesis described in the literature is the synthesis of the tricyclic trisanhydride (XXV) by the reaction of 6-bromomethyl-5-methyl-2-pyrone‡ with an excess of maleic anhydride at 140°C according to the following Scheme[51]:

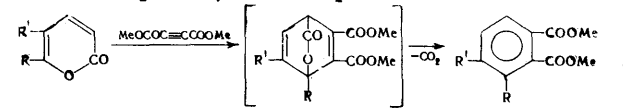


(XXV)

The above data illustrate the scope of diene synthesis with pyrones in the formation of polycyclic and "skeletal" systems.

2. Synthesis of Aromatic and Heterocyclic Compounds

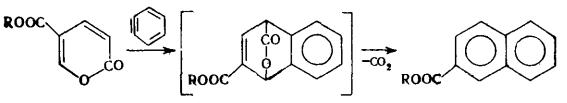
The formation of aromatic compounds by the reaction of 2-pyrones with acetylenic dienophiles was observed for the first time by Alder and Ricert[52]. The 1,4-cycloadducts produced initially in these reactions were not isolated, since they immediately split off the endoxycarbonyl bridge (because it is in the β-position with respect to two double bonds) and are converted into aromatic compounds, for example[53]:



The reaction of 2-pyrones with acetylenedicarboxylic acid ester resulted in the formation of satisfactory yields of hydroxy-,[52] dialkyl-,[53,54] and aryl-substituted[55] phthalic acids and hemimellitic acid[56] which are otherwise difficult to obtain. The reaction of diethylacetylene with 2-pyrone[57] to form *o*-diethylbenzene (yield 12%) proceeds with much more difficulty.

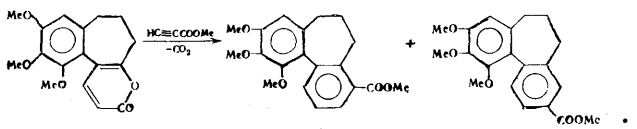
‡ The monoadduct was obtained from this pyrone at a temperature below 140°C.[5]

Derivatives of the naphthalene series have been obtained by the reaction of dehydrobenzene with alkyl coumalates [32]:

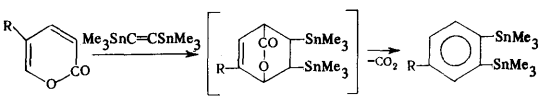


(R = Me, Et)

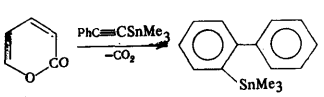
When asymmetric acetylenic dienophiles are used in reactions with 2-pyrones, the formation of a particular structural isomer is determined by polar and steric factors [58]. Thus the mode of addition of phenylacetylene to 2-pyrones is determined by the polar factor, since it proceeds in accordance with the charges of the initial reactants calculated by the Hückel method [58]. However, this rule breaks down when the dienophile employed is propiolic acid ester, which reacts with 2-pyrones to form both possible structural isomers [25,58], for example [25]:



New possibilities in the employment of diene synthesis with 2-pyrones have been discovered by Evnin and Seyferth [59]. To synthesis aromatic organotin compounds, they carried out the reaction of 2-pyrones with bis(trimethylstannyl)acetylene and trimethylphenylethynyltin:

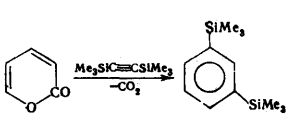


(R = H, Me, COOMe)



The study of the competing reactions of bis(trimethylstannyl)acetylene with 2-pyrone and 5-methoxycarbonyl-2-pyrone showed that only the less nucleophilic 5-methoxycarbonyl-2-pyrone reacts with the dienophile. This finding suggests that the interaction of 2-pyrones with bis(trimethylstannyl)acetylene proceeds via the inverse mechanism (cf. Section II, 1 and 2). [59]

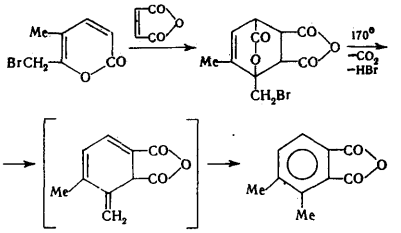
The use of bis(trimethylsilyl)acetylene in the reaction with 2-pyrone led unexpectedly to the formation of *m*-bis(trimethylsilyl)benzene as the main reaction product (53%) and only traces of the *o*- and *p*-isomers, which indicates the occurrence of a rearrangement [59]:



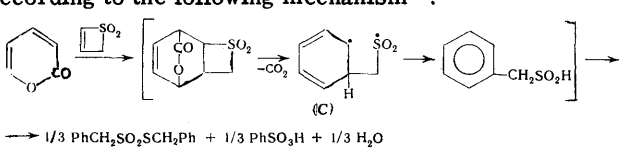
A special study [60] showed that the reason for the rearrangement is the acid-catalysed conversion of the *o*-isomer into the *m*-isomer. When acetylenic compounds of other Groups IV elements (tin and germanium) are used, such isomerisation does not take place, since the possible acid impurities are decomposed by these organometallic compounds as a result of the dissociation of the $M^{IV}-C$ bond, in agreement with the activity series of these metals (Sn ≥ Ge > Si) in protolytic reactions.

The authors admitted that the earlier explanation [59] of the above isomerisation as a result of the intermediate formation of non-Kekulé structures (prismane and benzvalene) is incorrect.

The formation of aromatic compounds in diene synthesis with 2-pyrones is possible for not only when acetylenic but also when ethylenic dienophiles are used, provided that together with the elimination of the bridge (CO_2) from the monoadduct, another simple molecule is also split off (hydrogen [32], hydrogen bromide [5], or an amine [18]), for example [5]:



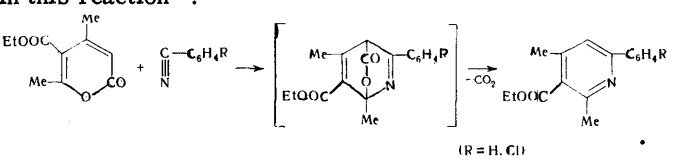
In the reaction of 2-pyrone with the sulphone derived from butadiene the resulting adduct also undergoes aromatisation in consequence of the elimination of CO_2 and the isomerisation of the biradical (C) to phenylmethanesulphinic acid, which disproportionates further according to the following mechanism [61]:



(C)

⟶ 1/3 $PhCH_2SO_2SCH_2Ph$ + 1/3 $PhSO_3H$ + 1/3 H_2O

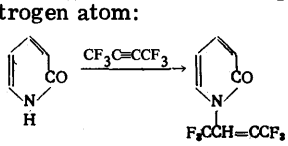
The interaction of 2-pyrones with nitriles via the mechanism of diene synthesis, accompanied by the elimination of CO_2 and the formation of substituted pyridines in a yield of about 20%, was described recently [62]. It is interesting that cyclones react similarly to nitriles, with the only difference that carbon monoxide is split off in this reaction [30]:



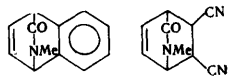
(R = H, Cl)

IV. DIENE SYNTHESIS WITH 2-PYRIDONES

The attempts to introduce 2-pyridones, nitrogen-containing analogues of 2-pyrones, into diene synthesis were unsuccessful for a long time. Pyridones unsubstituted at the nitrogen atom added to the double bonds of dienophiles (for example acrylonitrile [63], hexafluorobutyne [64], and acetylenedicarboxylic acid ester [65]) with formation of 2-pyridone derivatives alkylated or correspondingly vinylated at the nitrogen atom:



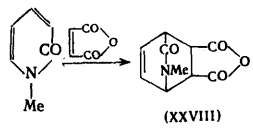
Among *N*-substituted 2-pyridones, only 1-methyl-2-pyridone could be made to undergo the diene synthesis reaction, giving rise to the adducts (XXVI) and (XXVII) respectively with dehydrobenzene [66,67] and fumarodinitrile [68] (yield 1–10%).



(XXVI) (XXVII)

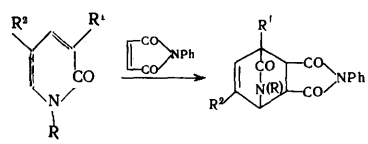
Owing to the low yields, the above reactions of 1-methyl-2-pyridone are of no preparative value. The 1,4-cycloadduct of this pyridone with tetracyanoethylene could not be obtained either [69].

In 1969 Japanese chemists obtained the adduct of 1-methyl-2-pyridone with maleic anhydride (XXVIII), in a yield of 42% (after heating for 72 h in toluene)§ [71,72], whose structure they demonstrated in detail both chemically and spectroscopically [72,73] (cf. the end of Section V).



(XXVIII)

Shusherina and coworkers succeeded in demonstrating that diene synthesis with 2-pyridones is a general reaction by employing *N*-phenylmaleimide and maleimide as dienophiles. It was found that not only do different *N*-substituted 2-pyridones form 1,4-cycloadducts (XXIX)—(XXXI) with these dienophiles in high yields [74,75], but also, and this is particularly interesting, even 2-pyridones unsubstituted at the nitrogen atom, whose interaction with other dienophiles gives rise to substitutional addition products only [63-65] (cf. the beginning of this Section) undergo this reaction to form Diels–Alder adducts (XXXII) and (XXXIII) in yields of about 50%: [76]



(XXIX–XXXIII)

(XXIX, R = Me, Pr, Bu, *i*-C_5H_{11}, H; R^1=R^2=H)
(XXX, R = Me, R^1 = H, R^2 = Me)
(XXXI, R = Me, R^1 = Me, R^2 = H)
(XXXII, XXXIII, R = R^1 = R^2 = H)

In contrast to the 2-pyrone adducts, the 1,4-cycloadducts of 2-pyridones {derivatives of 7-oxo-8-azabicyclo-[2,2,2]oct-4-ene-1,2-dicarboxylic acid} do not split off the bridge on thermolysis, but undergo retrodiene decomposition [75].

§ The cycloadduct could not be obtained by heating these reactants in benzene [70].

The results described indicate a lower diene reactivity of 2-pyridones compared with 2-pyrones. However, it is already evident that, by choosing a suitable dienophile, the Diels–Alder reaction can be widely employed in the series of 2-pyridones.

V. THE STEREOCHEMISTRY OF DIENE SYNTHESIS WITH 2-PYRONES AND 2-PYRIDONES

Like other cyclic dienes, 2-pyrones and 2-pyridones can give rise in reactions with dienophiles to monoadducts¶ with *endo*- and *exo*-configurations. The study of the *endo*–*exo* selectivity of diene synthesis, which was begun by Alder, has continued vigorously for more than 30 years. The interest in this subject is due to the employment of stereochemical data in the consideration of reaction mechanisms and transition state structures [1,77-80].

On the basis of experimental data obtained mainly in a study of diene synthesis with cyclopentadiene and its derivatives, Alder and Stein [81] concluded that the diene synthesis reactions are *endo*-stereoselective and formulated the so called Alder "*endo*-rule", which they accounted for by the possibility of the "maximum accumulation of unsaturation" only for the *endo*-orientation of the components. Further investigation of the stereochemistry of reactions between cyclic dienes and dienophiles with different structures revealed many exceptions to this rule. Thus doubt was cast on the *endo*-selectivity of diene synthesis discovered by Alder [82].

Different types of non-bonding (non-valence) or secondary-bonding interaction were considered as the main factors stabilising the *endo*- and *exo*-transition states [78-83]. The role of these forces in Diels–Alder reactions is much greater than in other processes owing to the "close packing" of the transition states, which promotes a greater proximity of the individual structural elements of the diene and dienophile [77].

Different versions of the concept, proposed at an early stage by Alder, of the overlapping of the π-orbitals of the multiple bonds of the diene and dienophile as the *endo*-orienting factor have been most widely discussed [78-81]. These ideas have now been confirmed theoretically by molecular orbital calculations and are used in the form of the Woodward–Hoffmann rule, correlating the secondary π-orbital interaction with orbital symmetry, to predict the steric course of cycloaddition reactions, including diene synthesis [84,85].

The important role of π-orbital interaction was demonstrated convincingly recently by the conversion of non-stereoselective Diels–Alder processes into *endo*-selective reactions by the introduction into the dienophile of a second and third double bond. Thus the reactions of 2,5-dimethyl-3,4-diphenylcyclopentadienone with non-conjugated mono-olefins (cyclopentene [86], *cis*-3,4-dichlorocyclobutene [87], and cycloheptene [88]), for which secondary π-orbital interaction is impossible, took place non-stereoselectively with formation of mixtures of *endo*- and *exo*-isomers, while the reactions with dienophiles having several multiple bonds (cyclopentadiene [86], tropone [86,89]

¶ The configurations of the bisanhydrides and bisimides, formed in diene synthesis, which were described above is not considered in this section since it is determined by the stereochemistry of the diene synthesis with cyclohexaidiene systems and not by the nature of the 2-pyrones (see Section III, 1).

and cycloheptatriene [86]) gave only the *endo*-isomers. Thus the *endo*-rule received new experimental confirmation in these investigations†.

However, the secondary π-orbital interaction can influence stereochemistry only in kinetically controlled reactions. In those cases where *endo*–*exo* isomerisation of the adducts is possible and the stereochemical result is not determined by kinetics but by the thermodynamic stability of the stereoisomers, the more stable *exo*-isomers are frequently formed (particularly at relatively high temperatures), for example in the reactions of furan and its derivatives with maleic anhydride [21,92–94]. Furthermore, in order to be able to play a decisive role in the orientation of the components, π-orbital interaction must be sufficiently strong, as in the reactions of cyclic dienes with cyclic dienophiles containing several unsaturated groups (for example, with maleic acid derivatives and quinones) [1]. On the other hand, reactions with dienophiles whose double bond is activated by only one unsaturated group can occur non-stereoselectively (for example, the interaction of cyclopentadiene with acrylonitrile) [95].

One should also bear in mind that, when the diene molecule contains two unsaturation centres (for example, in fulvenes) the π-orbital interaction promotes both possible orientations of the reactants [1,78].

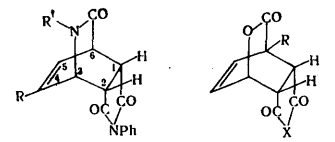
Together with π-orbital interaction, which occurs in the presence of additional unsaturated groups in the dienophiles, the stereochemistry of the reaction can be affected by saturated substituents of the diene and dienophile favouring the *endo*- or *exo*-approach of the reactants by the operation of electrostatic forces (attractive dispersion forces, repulsive van der Waals forces, and dipole–dipole interaction), which arise between the saturated diene and dienophiles substituents themselves and between the latter and the sp^2-carbon atoms of the diene [84,86]. The study of this factor, which can also be observed only under the conditions of kinetically controlled reactions, is made difficult by the fact that it may be determined by different types of interaction of the substituents some of which favour *endo*-selectivity and others favour *exo*-selectivity.

Studies on the effect of structural factors on the stereochemistry of diene synthesis have been made only recently [96–102]. For example, it has been established that the preferential formation of the *exo*-isomers in the reactions of cyclopentadiene with methacrylic acid and its derivatives is determined by the presence of the methyl group in the α-position of the dienophile [103–107]. It is at present difficult to decide [91] whether this is a consequence of the operation of repulsive forces between the hydrogen atoms of the methylene group of cyclopentadiene and the methyl group of the dienophile [101,107] or of attractive dispersion forces between the α-methyl group of the dienophile and the sp^2-carbon atoms of the diene [104,105].

The *endo*-selectivity of the reactions of cyclopentadiene with certain mono-olefins (cyclopropene, norbornene, allyl alcohol, and allyl bromide [108]) has been explained by the operation [86] of van der Waals forces.

It is evident from the data quoted that the problem of the *endo*–*exo*-selectivity of diene synthesis continues to remain controversial. More comprehensive investigation of various factors, particularly those determined by the structure of the dienophile, is necessary for its solution. In this sense the study of the stereochemistry of diene synthesis with 2-pyrones and 2-pyridones is of great interest.

The investigation by the present author (together with Levina, Stepanyants, and coworkers) of the configuration of the adducts of 2-pyrones with maleic anhydride and *N*-phenylmaleimide (by ^{1}H NMR‡ [6,16,109] and chemically [109,110], see below) and also of the adducts of *N*-alkylpyridones with *N*-phenylmaleimide by ^{1}H NMR‡ [74,75] showed that, in the absence of methyl groups at the ends of the conjugated system of multiple bonds of these heterocycles, the interaction with dienophiles proceeds *endo*-selectively with formation of the adducts (XXIX), (XXX), and (XXXIV)–(XXXVI).

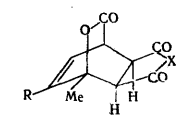


(XXIX, R = H, R^1 = Alk (Me, Pr, Bu, C_5H_{11})
(XXX, R = R^1 = Me)

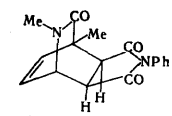
(XXXIV, R = H, X = O)
(XXXV, R = Br, X = O)
(XXXVI, R = H, X = NPh)

The interaction of the unsubstituted 2-pyrone with fulvene, discovered by Houk in 1973, also took place *endo*-stereoselectively [111].

On the other hand, 5,6-dimethyl-2-pyrone and 6-methyl-5-phenyl-2-pyrone form only *exo*-adducts with maleic anhydride and *N*-phenylmaleimide [(XXXVII)–(XXXIX)]. [6,16,109] A similar *exo*-influence of the methyl group in the 3α-position of the pyridone rings occurred in the interaction of 1,3-dimethyl-2-pyridone with *N*-phenylmaleimide, which led to the formation of the *exo*-adduct (XXXI) alone [75]:



(XXXVII, R = Me, X = O)
(XXXVIII, R = Ph, X = O)
(XXXIX, R = Me, X = NPh)



(XXXI)

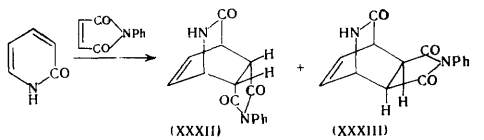
The observed breakdown of the Alder *endo*-rule for 5,6-disubstituted 2-pyrones and 1,3-dimethyl-2-pyridone cannot be due to thermal isomerisation, because the *exo*-adducts were obtained at the same (or lower) temperatures as the *endo*-adducts [16,109]. The effect of the secondary

† A fundamentally new explanation of the Alder *endo*-rule, based on the concept of the preferred geometry of the *endo*-overlapping of the π-orbitals of the carbon atoms of the diene and the dienophile directly involved in the formation of new bonds, was given by Herndon and Hall [90,91].

‡ The determination of the configuration of the adducts of 2-pyrones and 2-pyridones with maleic anhydride and *N*-methylmaleimide [(XXIX)–(XXXI) and (XXXIV)–(XXXIX)] by ^{1}H NMR [6,16,74–76,109] is based on the difference between the coupling constants of the protons at the bridgehead ($C_{(3)}H$ and $C_{(6)}H$) with the adjacent protons ($C_{(6)}H$ and $C_{(2)}H$) for the *endo*- and *exo*-isomers and also on the change in the chemical shifts of the $C_{(1)}H$, $C_{(2)}H$, and $C_{(6)}H$ protons for which the $C_{(1)}H$ and $C_{(2)}H$ signals of the *exo*-forms are in a higher field and those of the methine protons at the bridgehead ($C_{(6)}H$) are in a lower field compared with the signals of the corresponding protons in the spectra of the *endo*-forms.

π-orbital interaction, which determines the stereochemistry of the above Diels–Alder reactions with 2-pyrones [6,16,109] and *N*-alkyl-2-pyridones [74,75] unsubstituted at the ends of the conjugated system of multiple bonds, is probably suppressed in these heterocyclic dienes with 3- and 6-methyl [6,16,76,109] (or aryl [112,113]) groups, which favour the formation of *exo*-adducts.

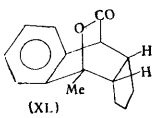
It is interesting that 2-pyridones unsubstituted at the nitrogen atom react with maleimide and *N*-phenylmaleimide via the Diels–Alder mechanism (cf. Section IV) non-stereoselectively with formation of a mixture of the *endo*-isomer (XXXII) and the *exo*-isomer (XXXIII). [76]



(XXXII) (XXXIII)

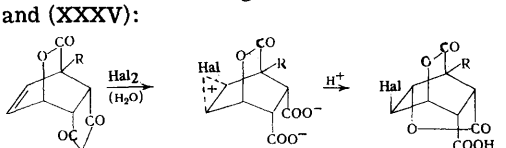
Thus the study of the stereochemistry of diene synthesis with 2-pyrones and 2-pyridones revealed for the first time the *exo*-orienting effect of the methyl and phenyl groups at the ends of the conjugated system of the heterocyclic diene in their interaction with maleic anhydride and *N*-phenylmaleimide.

However, in the reactions of 6-methyl-4,5-benzo-2-pyrone with nonconjugated dienophiles (cyclopentene, cycloheptene) the above influence of the methyl group was not observed: the reactions took place mainly with formation of the *endo*-adducts (XL), which the authors explained by the attraction of the methylene groups of the dienophile to the double bonds of the diene [114], as described above [104,105].



(XL)

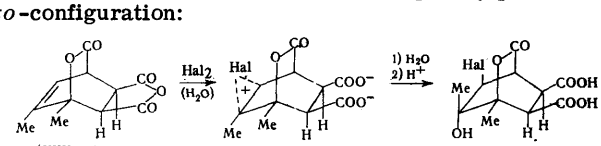
The use of chemical methods for the determination of the configuration of the adducts of 2-pyrones with maleic anhydride is based on the formation of different compounds from the *endo*- and *exo*-isomers on electrophilic addition to the double bond in the manner described for the adducts of other cyclic dienes with maleic anhydride [115–117]. Thus halogenation of the adducts (XXXIV) and (XXXV) in an aqueous medium yielded the halogenolactones (XLI)–(XLIV), formed as a result of the intramolecular stabilisation of the halogenonium ions produced initially [110,118], which confirms the *endo*-configuration of the adduct (XXXIV) and (XXXV):



(XXXIV, R = H)
(XXXV, R = Br)

(XLI, R = Br, Hal = Br)
(XLII, R = H, Hal = Cl)
(XLIII, R = H, Hal = Br)
(XLIV, R = H, Hal = I)

The formation of the halogenohydrins (XLV) and (XLVI) from the adduct (XXXVII) [110,118] demonstrates the impossibility of such stabilisation and consequently proves its *exo*-configuration:



(XXXVII)

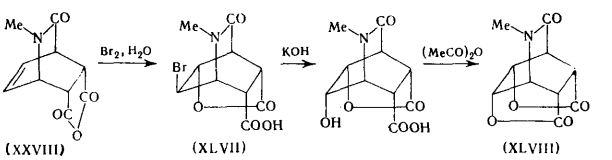
(XLV, Hal = Cl)
(XLVI. Hal = Br)

However, it is noteworthy that the halogenation of bridged bicyclic systems is accompanied by the Wagner–Meerwein rearrangement [92,119]. The formation of the isomeric halogenolactones from the *endo*- and *exo*-forms in such cases can lead to an incorrect interpretation of the stereochemistry of the reaction [92,120].

Since conclusions concerning the configuration of the adducts (XXXIV), (XXXV), and (XXXVII) based on the above reactions are consistent with ^{1}H NMR spectroscopic data (see above), one may conclude further that in the instances described the halogenation of the 2-pyrone adducts was not accompanied by a rearrangement.

The most reliable method for the determination of the configurations of bicyclic adducts—conversion into the iodolactone in which the possibility of the Wagner–Meerwein rearrangement is ruled out [121]—is unsuitable for the adducts of 2-pyrones with maleic anhydride, since the iodination of these systems takes place non-quantitatively and is accompanied by the rupture of the endoxycarbonyl bridge [118].

The *endo*-configuration of the adduct of 1-methyl-2-pyridone with maleic anhydride (XXVIII) (see Section IV) was established recently by the following series of transformations into the bromolactone (XLVII) and the bislactone (XLVIII): [71,72]



(XXVIII) (XLVII) (XLVIII)

The absence of the Wagner–Meerwein rearrangement in the bromination of the adduct (XXVIII) was demonstrated by the ^{1}H NMR spectra of the bromolactone (XLVII) and its deuteriated derivatives [73].

The data on the stereochemistry of diene synthesis with 2-pyrones and 2-pyridones described above show that the orientation of the components in these reactions is not determined solely by the secondary π-orbital interaction. Examples of the breakdown of the Alder rule when substituents are introduced in specific positions in the 2-pyrone [6,16,111] and 2-pyridone [75] rings and also the non-stereoselective course of the reactions with 2-pyridones unsubstituted at the nitrogen atom [76] are evidence for the important role of other factors, the nature of which will have to be elucidated in future investigations.

REFERENCES

1. A. S. Onishchenko, "Dienovyi Sintez" (The Diene Synthesis), Izd. Akad. Nauk SSSR, Moscow, 1963.
2. M. Ya. Karpeiskii and V. L. Florent'ev, Uspekhi Khim., 38, 1244 (1969) [Russ. Chem. Rev., No. 7 (1969)].
3. N. P. Shusherina, E. A. Luk'yanets, N. D. Dmitrieva, and R. Ya. Levina, Uspekhi Khim., 36, 437 (1967) [Russ. Chem. Rev., No. 3 (1967)].
4. O. Diels and K. Alder, Annalen, 490, 257 (1931).
5. N. P. Shusherina, E. Ya. Vashakidze, and R. Ya. Levina, Zhur. Org. Khim., 4, 1291 (1968).
6. N. P. Shusherina, M. V. Gapeeva, A. U. Stepanyants, D. M. Mondishka, and R. Ya. Levina, Zhur. Org. Khim., 7, 1383 (1971).
7. M. Goldstein and G. Thayer, J. Amer. Chem. Soc., 87, 1925 (1965).
8. R. Nicoletti, Ann. Chim. (Italy), 51, 1260 (1961).

9. J. Fried and R. Elderfield, J. Org. Chem., 6, 566 (1941).
10. L. Panizzi and R. Nicoletti, Ann. Chim. (Italy), 51, 1256 (1961).
11. N. P. Shusherina, M. Yu. Lur'e, and R. Ya. Levina, Dokl. Akad. Nauk SSSR, 109, 117 (1956).
12. N. P. Shusherina, R. Ya. Levina, Z. S. Sidenko, and M. Yu. Lur'e, Zhur. Obshch. Khim., 29, 403 (1959).
13. N. P. Shusherina, E. Ya. Vashakidze, and R. A. Levina, Zhur. Org. Khim., 5, 2227 (1969).
14. L. Holland and D. Jones, J. Chem. Soc. (C), 536 (1970).
15. L. Holland and D. Jones, J. Chem. Soc. (C), 530 (1970).
16. M. V. Gapeeva, A. U. Stepanyants, I. P. Shusherina, Yu. A. Knirel', and R. Ya. Levina, Zhur. Org. Khim., 7, 2426 (1971).
17. L. Fieser and M. Haddadin, J. Amer. Chem. Soc., 86, 2081 (1964).
18. H. Behringer and P. Heckmaier, Ber., 102, 2835 (1969).
19. W. Pirkle and L. McKendry, Tetrahedron Letters, 5279 (1968).
20. O. Schmidt, Chem. Rev., 17, 137 (1935).
21. H. Kwart and K. King, Chem. Rev., 68, 440 (1968).
22. N. P. Shusherina, E. Ya. Vashakidze, and R. Ya. Levina, Vestnik Moskov. Gos. Univ., No. 4, 473 (1971).
23. N. P. Shusherina, E. Ya. Vashakidze, M. V. Gapeeva, and R. Ya. Levina, Zhur. Org. Khim., 5, 1495 (1969).
24. R. Darms, T. Threlfall, M. Pesaro, and A. Eschenmoser, Helv. Chim. Acta, 46, 2893 (1963).
25. J. Schreiber, W. Leimgruber, M. Pesaro, P. Schudel, A. Threlfall, and A. Eschenmoser, Helv. Chim. Acta, 44, 540 (1961).
26. G. Märkl, Ber., 96, 1441 (1963).
27. N. P. Shusherina, E. Ya. Vashakidze, and R. Ya. Levina, Vestnik Moskov. Gos. Univ., No. 2, 241 (1971).
28. N. P. Shusherina, M. V. Gapeeva, and N. V. Gladkova, Zhur. Org. Khim., 8, 1083 (1972).
29. P. S. Zefirov and V. I. Sokolov, Uspekhi Khim., 36, 243 (1967) [Russ. Chem. Rev., No. 2 (1967)].
30. M. Ogliaruso, M. Romanelli, and E. Becker, Chem. Rev., 65, 261 (1965).
31. N. P. Shusherina, R. Ya. Levina, and I. S. Trubnikov, Zhur. Obshch. Khim., 29, 2942 (1959).
32. A. Bahl and W. Kemp, J. Chem. Soc. (C), 2268 (1971).
33. N. P. Shusherina, E. A. Luk'yanets, T. L. Tsilevich, and R. Ya. Levina, Zhur. Org. Khim., 2, 1202 (1966).
34. N. P. Shusherina, I. D. Dmitrieva, G. V. Komarovskaya, and R. Ya. Levina, Zhur. Org. Khim., 4, 2048 (1968).
35. N. D. Dmitrieva, A. D. Moiseeva, N. P. Shusherina, V. D. Shumakova, and R. Ya. Levina, Zhur. Org. Khim., 4, 1477 (1968).
36. A. N. Akopyan and A. M. Saakyan, "Sbornik Dokladov IV Vsesoyuznoi Konferentsii po Khimii Atsetilena" (Collected Reports at the IVth All-Union Conference on Acetylene Chemistry), Alma-Ata, 1972, Vol. I, p. 127.
37. J. Bu'Lock and H. Smith, J. Chem. Soc., 502 (1960).
38. N. P. Shusherina, N. D. Dmitrieva, and R. Ya. Levina, Dokl. Akad. Nauk SSSR, 146, 1113 (1962).
39. N. P. Shusherina, N. D. Dmitrieva, and R. Ya. Levina, Dokl. Akad. Nauk SSSR, 126, 589 (1959).
40. N. P. Shusherina, N. D. Dmitrieva, T. F. Kozlova, and R. Ya. Levina, Zhur. Obshch. Khim., 30, 2829 (1960).
41. N. P. Shusherina, N. D. Dmitrieva, N. N. Malysheva, and R. Ya. Levina, Zhur. Org. Khim., 2, 1120 (1966).
42. L. I. Zakharkin and L. P. Sorokina, Izv. Akad. Nauk SSSR, Ser. Khim., 870 (1965).
43. T. Kealy, J. Amer. Chem. Soc., 84, 966 (1962).
44. F. Baker and Z. Stock, J. Org. Chem., 32, 3344 (1967).
45. H. Zimmermann and R. Paufler, J. Amer. Chem. Soc., 82, 1514 (1960).
46. H. Zimmermann, G. Grunewald, and R. Paufler, J. Amer. Chem. Soc., 91, 2330 (1969).
47. P. Arora and D. Mackey, Chem. Comm., 677 (1969).
48. A. Krantz and C. Lin, Chem. Comm., 1287 (1971).
49. T. Imagava and M. Kawanisi, Chem. Comm., 1292 (1971).
50. T. Imagava, N. Sueda, and M. Kawanisi, Chem. Comm., 388 (1972).
51. N. P. Shusherina, E. A. Luk'yanets, and R. Ya. Levina, Zhur. Org. Khim., 1, 1502 (1965).
52. K. Adler and H. Rickert, Ber., 70, 1354 (1937).
53. N. P. Shusherina, R. Ya. Levina, and V. M. Shostakovskii, Zhur. Obshch. Khim., 29, 3277 (1959).
54. T. Jaworski and S. Kwiatkowski, Roczniki Chem., 44, 555 (1970).
55. A. Padwa and R. Harman, J. Amer. Chem. Soc., 88, 3759 (1966).
56. E. Wenkert, D. Johnston, and R. Dave, J. Org. Chem., 29, 2534 (1964).
57. D. White and D. Seyferth, J. Org. Chem., 37, 3545 (1972).
58. J. Reed, C. Schilling, R. Tarwin, T. Retting, and J. Stille, J. Org. Chem., 34, 2188 (1969).
59. A. Evnin and D. Seyferth, J. Amer. Chem. Soc., 89, 952, 4793 (1967).
60. D. Seyferth and D. White, J. Organometal. Chem., 34, 119 (1972).
61. J. McCaskie, T. Nelson, and D. Dittmer, J. Org. Chem., 38, 3048 (1973).
62. T. Jaworski and S. Kwiatkowski, Roczniki Chem., 44, 691 (1970).
63. R. Adams and A. Schrecker, J. Amer. Chem. Soc., 71, 1186 (1949).
64. L. Paquette, J. Org. Chem., 30, 2107 (1965).
65. R. Acheson and P. Tasker, J. Chem. Soc. (C), 1542 (1967).
66. L. Bauer, C. Bell, and G. Wright, J. Heterocycl. Chem., 3, 393 (1966).
67. E. Sheinin, G. Wright, C. Bell, and L. Bauer, J. Heterocycl. Chem., 5, 859 (1968).
68. H. Tomisawa, R. Fujita, K. Noguchi, and H. Hongo, Chem. Pharm. Bull. (Tokyo), 18, 925 (1970).
69. B. Thyagarijan, K. Rajagopolan, and P. Gopalakrishnar, J. Chem. Soc. (B), 300 (1968).
70. B. Thyagarijan, and K. Rajagopolan, Tetrahedron, 19, 1483 (1963).
71. H. Tomisawa and H. Hongo, Tetrahedron Letters, 2465 (1969).
72. H. Tomisawa and H. Hongo, Chem. Pharm. Bull. (Tokyo), 18, 941 (1970).
73. H. Hongo, Chem. Pharm. Bull. (Tokyo), 20, 226 (1972).
74. N. P. Shusherina and M. V. Gapeeva, Zhur. Org. Khim., 9, 848 (1973).
75. N. P. Shusherina, L. V. Betaneli, G. B. Mndlyan, and A. U. Stepanyants, Khim. Geterotsikl. Soed., No. 10 (1974).
76. N. P. Shusherina, L. V. Betaneli, and A. U. Stepanyants, Dokl. Akad. Nauk SSSR, 213, 115 (1973).

77. R. Griger and C. Eckert, J. Amer. Chem. Soc., **92**, 7149 (1970).
78. J. Martin and R. Hill, Chem. Rev., **61**, 537 (1961).
79. S. Seltzer, "Advances in Alicyclic Chemistry", New York–London, 1968, Vol. 2.
80. J. Sauer, Angew. Chem., **79**, 76 (1967).
81. K. Alder and G. Stein, Angew. Chem., **50**, 510 (1937).
82. C. K. Ingold, "Theoretical Foundations of Organic Chemistry" (Translated into Russian), Izd. Mir, Moscow, 1973, p. 895.
83. A. Wassermann, "The Diels–Alder R action" (Elseview, New York, 1965) (Translated into Russian), Izd. Mir, Moscow, 1968.
84. R. Hoffmann and R. Woodward, J. Amer. Chem. Soc., 87, 4388 (1965).
85. G. B. Gill, Quart. Rev., **22**, 338 (1968).
86. K. Houk, Tetrahedron Letters, 2621 (1970).
87. C. Anderson, J. McCay, and R. Warrener, Tetrahedron Letters, 2735 (1970).
88. K. Houk and R. Woodward, J. Amer. Chem. Soc., **92**, 4193 (1970).
89. K. Houk and R. Woodward, J. Amer. Chem. Soc., **92**, 4145 (1970).
90. W. Herndon and L. Hall, Tetrahedron Letters, 3095 (1967).
91. W. Herndon, Chem. Rev., **72**, 173 (1972).
92. R. Woodward and H. Bear, J. Amer. Chem. Soc., **70**, 1161 (1948).
93. H. Kwart and J. Burchuk, J. Amer. Chem. Soc., **74**, 3094 (1952).
94. N. S. Zefirov, R. I. Ivanova, and Yu. K. Yur'ev, Zhur. Obshch. Khim., 35, 58 (1965).
95. K. Alder, W. Günyl, and K. Wolff, Ber., 93, 809 (1960).
96. K. Williamson, Yuan-Fang Li Hsu, R. Lacko, and Ch. Youn, J. Amer. Chem. Soc., **91**, 6129 (1969).
97. B. Jacobson, J. Amer. Chem. Soc., **95**, 2579 (1973).
98. K. Williamson and Li Hsu, J. Amer. Chem. Soc., **92**, 7385 (1970).
99. B. Trost, J. Amer. Chem. Soc., **91**, 918 (1969).
100. R. La Rochell and B. Trost, Chem. Comm., 1353 (1970).
101. K. Houk and L. Luskus, J. Amer. Chem. Soc., **93**, 4606 (1971).
102. E. Garbisch and R. Sprecher, J. Amer. Chem. Soc., **91**, 6785 (1969).
103. Y. Berson, Z. Hamlet, and W. Mueller, J. Amer. Chem. Soc., **84**, 297 (1962).
104. Y. Kobuke, T. Sugimoto, and J. Turukawa, J. Amer. Chem. Soc., **94**, 3633 (1972).
105. Y. Kobuke, T. Fueno, and J. Turukawa, J. Amer. Chem. Soc., **92**, 6548 (1970).
106. E. McBee, M. Klogh, R. Levek, and E. Wesseler, J. Org. Chem., 38, 632 (1973).
107. A. I. Konovalov, G. I. Kamasheva, and M. P. Loskutov, Zhur. Org. Khim., 8, 2048 (1973).
108. N. A. Belikova, V. G. Berezkin, and A. F. Plate, Zhur. Obshch. Khim., **32**, 2896 (1962).
109. E. Ya. Vashakidze, N. P. Shusherina, A. U. Stepanyants, D. M. Mondishka, and R. Ya. Levina, Zhur. Org. Khim., 6, 1918 (1970).
110. N. P. Shusherina, M. V. Gapeeva, and R. Ya. Levina, Zhur. Obshch. Khim., **40**, 1418 (1970).
111. K. Houk and L. Luskus, J. Org. Chem., **38**, 3836 (1973).
112. D. Jones and R. Wife, Chem. Comm., 421 (1973).
113. D. Jones and R. Wife, J. Chem. Soc. Perkin I, 2722 (1972).
114. D. Jones and G. Kneen, Chem. Comm., 420 (1973).
115. K. Alder and G. Stein, Annalen, **514**, 197 (1934).
116. J. Berson and R. Swidler, J. Amer. Chem. Soc., **75**, 1721 (1953).
117. I. N. Nazarov, V. F. Kucherov, and V. G. Bukharov, Izv. Akad. Nauk SSSR, Ser. Khim., 192 (1958).
118. N. P. Shusherina and M. V. Gapeeva, Zhur. Org. Khim., 9, 1190 (1973).
119. Yu. K. Yur'ev and N. S. Zefirov, Zhur. Obshch. Khim., 32, 773 (1962).
120. K. Alder and H. Backendorf, Annalen, **535**, 101 (1938).
121. H. Stockmann, J. Org. Chem., **26**, 2025 (1961).

Faculty of Chemistry,
Lomonosov
Moscow State University