RUSSIAN CHEMICAL REVIEWS
Uspekhi Khimii

May 1962

ORIENTATION IN DIENE SYNTHESIS AND ITS DEPENDENCE ON STRUCTURE

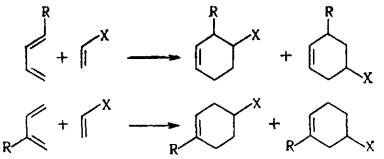
Yu. A. Titov

CONTENTS

1.	Introduction	267
2.	1-Substituted dienes	268
3.	2-Substituted dienes	269
4.	Disubstituted dienes	272
5.	Trisubstituted dienes	273
6.	Disubstituted dienophiles	274
7.	Cyclic dienes	275
8.	Dimerisation of monosubstituted dienes	276
9.	Dienes and dienophiles containing heteroatoms	276
10.	Structural directivity and mechanism of diene synthesis	277

1. INTRODUCTION

In any practical application of diene synthesis — from the preparation of the simplest cyclohexane derivatives to the building up of complicated steriod systems — the mutual orientation of diene and dienophile during the reaction is of paramount significance. One of the most important aspects of this question — structural directivity — is shown in the condensation of unsymmetrical dienes and dienophiles. As can be seen from the scheme below, two pairs of structural isomers — *ortho*† and *meta* with 1-substituted dienes, and *para* and *meta* with 2-substituted dienes — can theoretically be formed.



Available experimental data show that in the first case *ortho*-adducts predominate, and in the second *para*-adducts: *i.e.* the reaction exhibits quite definite structural selectivity.

The study of this dependence of orientation on structure has passed through several stages. For about twenty years after the reaction was discovered it was assumed that diene synthesis takes place without structural ambiguity, only one of the two theoretically possible isomers being formed in any particular case. During 1948–1949 it proved possible to isolate a second structural isomer from among the reaction products obtained with penta-1,3-diene and with isoprene; this result was later extended to dienes having other types of substituents, such as C_6H_5, Cl, CH_3O, etc. Finally, much attention has been paid recently to determining the way in which the proportions of structural isomers depend on the structure of the reactants and the reaction conditions.

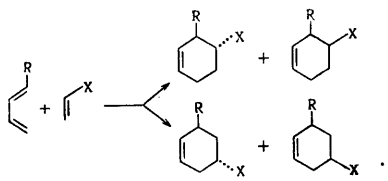
Most of the experimental results on structural directivity have accumulated during the past 8–10 years, and have not been covered by reviews on diene synthesis[1-4]. The present survey, which covers the literature up to the beginning of 1961, represents an attempt to fill this gap. In view of the very large number of diene condensations which have been carried out between unsymmetrical reactants, only work in which the structure of at least one of the isomers has been *proved* is included in the review.

† The terms *ortho*, *meta*, and *para* are now generally accepted for the structurally isomeric adducts of diene synthesis, although strictly they are applicable only to benzene derivatives.

2. 1-SUBSTITUTED DIENES

1-Substituted dienes can exist in the form of two geometrical isomers, corresponding to the *cis*- and *trans*--positions of the substituent. Dienes having the substituent in the *cis*-position are extremely difficult to condense even with the most active dienophiles. Thus the *cis*-1-substituted butadiene derivatives in which the substituent is the methoxycarbonyl[5,6], phenyl[7,8], chloro[9], and cyano[10] group hardly condense at all with maleic anhydride, while *cis*--penta-1,3-diene reacts with it only under very severe conditions[11]. All the condensations described in this section therefore relate solely to the *trans*-isomers of the dienes.

Formation of both *ortho*- and *meta*-adducts is possible in the condensation of *trans*-1-substituted dienes with unsymmetrical dienophiles. Each of them can in turn exist in the form of two geometrical isomers with the substituents in the *cis*- and *trans*-positions, which makes direct separation of the reaction products considerably more difficult.



In this and subsequent sections the published data will be discussed according to the types of substituents in the diene.

The structure of the adducts from condensations of *1-alkylbutadienes* is usually determined by dehydrogenation to the aromatic compounds, which are then converted to known products by various methods (hydrolysis, oxidation, etc.). The proportions of the structural isomers are estimated by fractional crystallisation either of the adducts themselves or of their dehydrogenation products, but this method gives only a semi-quantitative idea of the composition of the mixture.

The early work had already shown that in a large number of cases the main product of the reaction is the *ortho*--isomer. This isomer was obtained in the condensation of penta-1,3-diene with acrylic acid and its derivatives (esters and the nitrile)[12-17], citraconic anhydride[18], and acrolein[12,16,17,19,20]. Condensations of the same diene with acetylenic dienophille — propiolic acid[21,22] and aldehyde[23], ethynyl methyl ketone[24] — also yielded the *ortho*-adducts.

The formation of a ***mixture*** of structural isomers was established in 1940 in the condensation of penta-1,3-diene with toluquinone[25]. Somewhat later it proved possible to demonstrate the presence of the *meta*-isomer in a mixture of adducts of the same diene with acrylonitrile[26]. The *meta*-isomers were then isolated in the reaction of penta--1,3-diene with acrylic, methacrylic, and 2-isopropylacrylic esters, and also with styrene and acrolein (see Table 1).

Other 1-alkylbutadienes studied were the isopropyl, butyl, and t-butyl compounds, which have been condensed with acrylic acid and esters of α-substituted acrylic acids[27-29]. Both *ortho*- and *meta*-isomers were isolated in all cases, and their relative proportions determined.

1-Phenylbutadiene forms *ortho*-adducts when condensed with acrylic acid and its derivatives[30-36], and also with propiolic[35] and itaconic[37] acids, citraconic anhydride[37], acrolein[30-32,38], and methyl vinyl ketone[36,39]. The presence of *meta*-isomers was demonstrated only in the condensation of this diene with methyl acrylate, methyl methacrylate, and also styrene[40].

TABLE 1. Condensation of 1-substituted dienes with unsymmetrical dienophiles.

Diene $CH_2=CHCH=CH$ (R)	Dienophile $CH_2=C(R_1)R_2$ R_1	R_2	Reaction conditions, t, °C/h	Yield of adducts, %	*ortho*/*meta* ratio	References
CH_3	CHO	H	—	—	6 : 1	57
CH_3	CHO	H	—	—	8 : 1	58
CH_3	CN	H	100/24	56	7.3 : 1	26
CH_3	CN	H	100/12	30	10 : 1	59
CH_3	CO_2CH_3	H	230/2	82	5.2 : 1	59
CH_3	CO_2CH_3	H	200/2	85	6.8 : 1	28
CH_3	CO_2CH_3	CH_3	200/3	52	10.5 : 1	59
CH_3	CO_2CH_3	CH_3	200/2	68	5 : 1	28
CH_3	$CO_2C_2H_5$	iso-C_3H_7	200/15	33	2.5 : 1	28
CH_3	C_6H_5	H	200/2	41	6 : 1	59
iso-C_3H_7	CO_2CH_3	H	200/5	60	5 : 1	28
iso-C_3H_7	CO_2CH_3	CH_3	200/5	52	3.1 : 1	28
iso-C_3H_7	$CO_2C_2H_5$	iso-C_3H_7	200/10	32	2.4 : 1	28
n-C_4H_9	CO_2CH_3	H	200/5	74	5.1 : 1	28
t-C_4H_9	CO_2CH_3	H	160/5	60	3 : 1	27
t-C_4H_9	CO_2CH_3	H	200/5	76	4.1 : 1	28
t-C_4H_9	CO_2CH_3	CH_3	200/5	75	2.6 : 1	28
t-C_4H_9	$CO_2C_2H_5$	iso-C_3H_7	200/10	19	0.9 : 1	28
$OCOCH_3$	citraconic anhydride		100/4	59	1.5 : 1	47
$OCOCH_3$	xyloquinone		100/3	55	1.5 : 1	48
OCH_3	xyloquinone		110/1	62	10 : 1	48
C_6H_5	CO_2CH_3	H	150/3	61	39 : 1	40
C_6H_5	CO_2CH_3	CH_3	150/3	38	13 : 1	40
C_6H_5	C_6H_5	H	150/50	33	8.1 : 1	40
CO_2H	CO_2H	H	150/6	86	8.8 : 1	56
CO_2H	C_6H_5	H	150/6	58	5.7 : 1	56

Derivatives of 1-phenylbutadiene containing various substituents in the benzene ring have also been subjected to diene synthesis. The reactions of 1-*p*-bromophenyl- and 1-*p*-nitrophenyl-butadiene with acrylic acid, propiolic acid, and acrolein yielded only the *ortho*-isomers[41,42]. Condensation of 1-*o*-nitrophenylbutadiene with acrylic acid and acrolein also gave only one structural isomer, the *ortho*--orientation of the substituents in which was proved by conversion of the compounds to phenanthridine[43].

Condensation of *1-acetoxybutadiene* with acrylic acid[44] and with acrolein[45] yields only the *ortho*-adducts, whose structure was proved by conversion to 2-oxocyclohexanecarboxylic acid, whereas its reaction with 5-hydroxy-1,4--naphthaquinone yields a mixture of the two structural isomers[46]. The reactions of 1-acetoxybutadiene with citraconic anhydride[47] and xyloquinone[48] result in the formation of a mixture of *ortho*- and *meta*-isomers in which there is a slight preponderance of the former. The difference between acrylic acid and acrolein on the one hand and citraconic anhydride and xyloquinone on the other, revealed by this work, can be explained by the fact that the methyl group, being the only unsymmetrical feature in the latter two dienophiles, has little influence on the relative proportions of the structural isomers. Another factor is evidently the comparatively weak orienting effect of the acetoxy--group in the diene. In this connection it is interesting that the condensation of 1-methoxy- and 1-ethoxy-butadiene with xyloquinone shows a far more marked structural selectivity. In the former case only ~10% of the *meta*--adduct could be isolated, and in the latter the *ortho*-adduct alone was obtained[48].

Investigation of the adducts of *1-diethylaminobutadiene* is made quite difficult by their ready deamination even during the diene condensation itself[49]. However, by carrying out the reaction under mild conditions (in benzene solution at room temperature), it proved possible to obtain adducts in which the amino-group was preserved. Condensation of 1-diethylaminobutadiene with ethyl acrylate, acrylonitrile, and acrolein under these conditions[50] led to the formation of the *ortho*-isomers, the structure of which was proved by hydrogenation to known compounds.

Condensation of *1-cyanobutadiene* with methyl and ethyl acrylates resulted in the isolation of the *ortho*-isomers alone, which were converted to phthalic acid by dehydrogenation with *N*-bromosuccinimide followed by hydrolysis[51].

The *ortho*-adducts were isolated in the condensation of *butadiene-1-carboxylic acid* with acrylic acid[52] and with 1-vinylnaphthalene[53]. The same isomer was obtained by the interaction of butadiene-1-carbonyl chloride and acryloyl chloride[52]. When, however, the reaction was carried out between the anions of these acids (between salts of the acids in aqueous solution), roughly equal amounts of *ortho*- and *meta*-isomers were isolated[54]. This result was explained by repulsion between ions having like charges, and also by a decrease in orienting power on passing from COOH to COO^-. It has recently been shown that small amounts of the *meta*-isomer are present also in the condensation of butadiene-1-carboxylic acid with acrylic acid and with styrene[55,56].

---o0o---

Examination of published data on the condensation of 1-substituted dienes with unsymmetrical dienophiles shows that in all cases the *ortho*-isomers preponderate in the resulting mixtures of adducts. This has been established both with ethylenic and acetylenic dienophiles and with unsymmetrical quinones. The preferential formation of the *ortho*-isomers has been demonstrated for the following substituents: in the diene — R (alkyl), C_6H_5, $C_6H_4NO_2$, C_6H_4Br, CN, COOH, OR, CH_3COO, and $N(C_2H_5)_2$; and in the dienophile — COOH, COCl, $CONH_2$, CHO, CN, COR, and C_6H_5. Nevertheless, in some condensations it was possible to isolate the *meta*-isomers from the mixture of adducts, and to prove their structure (see Table 1).

The introduction of different substituents into the diene and the dienophile influences the relative proportions of the structural isomers in different ways. The more one isomer preponderates in the mixture of adducts formed, the greater the "orienting power" of the substituents is taken to be. The data in Table 1 show that, with a phenyl substituent in the 1-position of the diene, the *ortho*-isomer is formed almost exclusively, while on passing to carboxyl and methyl the amount of this isomer in the mixture successively decreases. Therefore these substituents can be arranged in the sequence $C_6H_5 > COOH > CH_3$ according to their orienting power. On condensation with xyloquinone 1-acetoxybutadiene forms considerably less of the *ortho*-isomer than does 1-methoxybutadiene, so that $CH_3O > > CH_3COO$ in orienting power.

These sequences in order of orienting power, derived purely empirically, are determined by a complex interaction between electronic and steric effects of the substituents in the diene and the dienophile, and it is in general extremely difficult to separate these effects. However,

TABLE 2. Ratio of *ortho*-to *meta*-isomers in condensations of 1-alkylbutadiences (at 200°)[29].

Diene	Dienophile: $CH_2=CHCOOCH_3$	Dienophile: $CH_2=C(CH_3)COOCH_3$	Dienophile: $CH_2=C(CH(CH_3)_2)COOC_2H_5$
$CH=CHCH=CH_2$, CH_3	6.8 : 1	4.9 : 1	2.5 : 1
$CH=CHCH=CH_2$, $CH(CH_3)_2$	5.0 : 1	3.1 : 1	2.4 : 1
$CH=CH-CH=CH_2$, C_4H_9	5.1 : 1	—	—
$CH=CHCH=CH_2$, $C(CH_3)_3$	4.1 : 1	2.6 : 1	0.9 : 1

the role of the steric factor can be quite clearly demonstrated by comparing the condensation of dienes and dienophiles containing alkyl substituents which differ greatly in bulk. The data in Table 2 show that, in condensations of 1-alkylbutadienes with esters of substituted acrylic acids, the change from methyl to t-butyl in the diene and from hydrogen to isopropyl in the dienophile results in an increased content of the *meta*-isomer in the mixture of adducts. This phenomenon must be explained by steric effects, since increase in the steric repulsion of the substituents with increase in their volume should yield a higher proportion of the *meta*-isomers, whose formation takes place in this case *via* sterically less hindered transition complexes[60,61].

Comparison of the condensation of penta-1,3-diene with acrolein and methyl acrylate (Table 1) at different temperatures suggests that structural directivity is influenced by the temperature of the reaction. This hypothesis has recently been verified with the latter dienophile[28]. The ratio of *ortho*- to *meta*-isomer was found to be 18 : 1 when reaction took place at 20°, 6.8 : 1 at 200°, and only 3.7 : 1 at 400°. Thus the proportion of the *meta*-isomer in the mixture of adducts increases as the temperature of the reaction rises. If we neglect the difference in steric effects in the formation of the structural isomers, this temperature dependence of orientation could be explained by the activation energy in the formation of the *ortho*-isomer being in this case 1.5 kcal $mole^{-1}$ lower than with the *meta*-isomer[61].

3. 2-SUBSTITUTED DIENES

As stated in the Introduction, condensation of 2-substituted dienes with unsymmetrical dienophiles can result in *para*- and *meta*-adducts. Up to the present time, structural directivity has been investigated in more than a hundred examples of such condensations, although in most cases it has proved possible to isolate and characterise only the *para*-adduct.

Diene condensations involving *isoprene* have been studied especially thoroughly owing to its ready availability. The *para*-isomer has been isolated from the reaction products and its structure proved in condensations with acrylic acid and its derivatives[13,62-65], and also acrolein[19,62,63], 2-ethylacrolein[66], and chloromethyl vinyl ketone[67]. The *para*-adduct alone was obtained in the condensation of isoprene with ethylenesulphonyl chloride[68], 2-vinylpyridine[69], and *p*-nitrophenylmaleic anhydride[70]. Acetylenic dienophiles

react similarly to the ethylenic compounds with isoprene: thus *para*-adducts are formed by propiolic acid and its derivatives[22,65], propynal[23], and ethynyl methyl ketone[24].

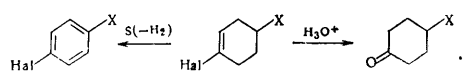
Nevertheless, in several cases it has proved possible to observe *meta*-isomers among the adducts, sometimes in considerable quantities. Thus isoprene forms ~20% of the *meta*-isomer with acrylonitrile[71] and methyl acrylate[62], and up to 40% with ethyl methacrylate[72]. Mixtures of the two isomers were also obtained in the condensation of isoprene with acrolein[57], esters of 2-substituted acrylic acids[59,73], styrene[69], 1-naphthylmaleic anhydride[74], and 2-methoxy-5-methylbenzoquinone[14].

Structural directivity has been studied in the condensations of other 2-alkylbutadienes, namely the ethyl, propyl, isopropyl, and t-butyl compounds. Their condensation with acrylic acid[27], esters of 2-substituted acrylic acids[75], and also phenylmaleic[76] and naphthylmaleic[74] anhydrides resulted in the formation of mixtures of the two structural isomers (see Table 3); with *p*-nitrophenylmaleic anhydride[70], however, only the *para*-adducts could be isolated. The condensation of myrcene with acrylic acid and its nitrile[77-79] and also with acrolein and methacrolein[78] led to the formation of mixtures of adducts having the same ratio, 4:1, of *para*- to *meta*-isomers; but condensation with vinyl acetate[80] gave only the *para*-adduct.

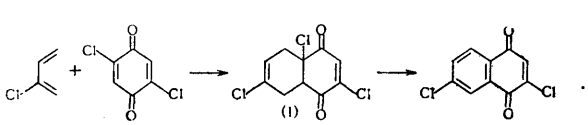
2-Phenylbutadiene yielded only *para*-adducts in most of its diene condensations. The *para*-structure has been proved for adducts of this diene with acrylic acid[81], methyl acrylate[82], acrolein[81,82], styrene[55,81], and phenylacetylene[82]. Nevertheless, it has proved possible to isolate up to 20% of the *meta*-isomer from the mixtures of adducts formed by 2-phenylbutadiene with dienophiles of the type of acrylic acid (see Table 3)[55,82].

Exclusive formation of the *para*-isomers has been noted in the condensation of 2-*p*-methoxyphenylbutadiene with acrylic acid, methyl methacrylate, and methyl vinyl ketone[83,84].

Proof of the structure of the adducts formed by *2-halogenobutadienes* with unsymmetrical dienophiles was based either on their dehydrogenation to known halogenated aromatic compounds[85,86] or on their hydrolysis with concentrated sulphuric acid to the corresponding ketones[40,87]:



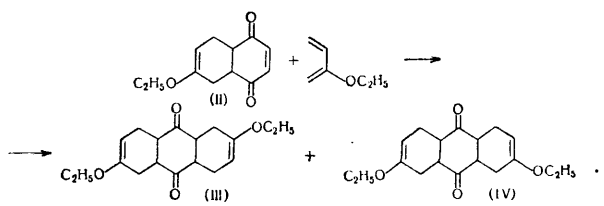
The formation of *para*-adducts has been demonstrated in the condensation of chloroprene with acrylic acid and various of its derivatives[85,86,88], ethyl ethylenesulphonate[89], acrolein[90], and 2-methylpropenyl vinyl ketone[87]. Among acetylenic dienophiles which form *para*-adducts with chloroprene are propynal[91], ethynyl methyl ketone[90], and propiolic acid[22] and its nitrile[65]. Only the *para*-adduct (I) could be isolated after condensation of chloroprene with 2,5-dichlorobenzoquinone, its dehydrogenation yielding 2,7-dichloronaphthaquinone[92]:



The *para*-orientation of the substituents has been proved also for the adducts of other 2-halogenated butadienes — bromoprene and fluoroprene — with propynal[91], and also for the condensate of fluoroprene with ethynyl methyl ketone[93]. The *meta*-isomers could be isolated only from the condensation of chloroprene with acrylic acid and with styrene[55,94].

2-Methoxybutadiene and *2-ethoxybutadiene* form adducts which are readily hydrolysable ethers of enols, and therefore the usual method for determining their structure is to hydrolyse them to known substituted cyclohexanones.

In general only *para*-adducts could be isolated from condensations of 2-alkoxybutadienes with acetylenic and ethylenic dienophiles, for example with esters of acrylic acid and its homologues[83,86,95,96], acrylonitrile[97], dimethyl mesaconate[98], and citraconic anhydride[98]. Reactions with carbonyl compounds — acrolein[99,100], propynal[91], and methyl vinyl[101], ethynyl methyl[102], and 2-methylpropenyl vinyl[87] ketones‡ — also resulted in the *para*-adducts. The *meta*-isomers could be isolated only from the condensation of 2-alkoxybutadienes with acrylic acid, styrene[55,94], and a few cycloalkenones[103,104]. There are indications that 2-alkoxybutadienes form mixtures of structural isomers also with toluquinone, thymoquinone[105], and 5-methoxy-1,4-naphthaquinone[106]. An interesting condensation is that of the monoadduct (II) of 2-ethoxybutadiene and benzoquinone with a second molecule of the diene, which yields a mixture of the isomers (III) and (IV) in the ratio 7:1.[107] Thus even an unsymmetrical feature which is remote from the reactive centres and is not conjugated with them can have a strong influence on the diene synthesis orientation:



Structural orientation in the reactions of 2-cyanobutadiene with methyl vinyl ketone and with acrylonitrile was studied[108]. In both cases the *para*-isomer alone was obtained, its structure being proved by conversion to terephthalic acid.

From the above survey of the literature it is evident that structural directivity in the condensation of 2-substituted dienes with unsymmetrical dienophiles has been studied with a great variety of substituents in the reactant molecules. Thus the dienes contained the substituents R (alkyls), C_6H_5, $CH_3OC_6H_4$, F, Cl, Br, OR, HCOO, and CN; and the dienophiles COOH, COCl, $CONH_2$, COR, CHO, CN, SO_2Cl, CH_3COO, C_6H_5, 1-naphthyl, and 2-pyridyl. In all these condensations the main reaction product proved to be the *para*-isomer. In several cases, however, the presence among the adducts of a certain amount of the *meta*-isomer could be established, and its structure proved (see Table 3).

It follows from Table 3 that the presence of the *meta*-isomer has been proved with almost all types of substituents in the diene. For the condensation of 2-substituted dienes with acrylic acid, we can arrange the substituents in the diene in the following sequence according to orienting

‡ The *para*-adduct alone was isolated from the condensation of 2-formyloxybutadiene with this dienophile[87].

TABLE 3. Condensations of 2-substituted dienes with unsymmetrical dienophiles.

Diene $CH_2=CRCH=CH_2$	Dienophile $CH_2=C(R_1)(R_2)$		Reaction conditions, t, °C/h	Yield of adducts, %	*para/meta* ratio	References
R	R_1	R_2				
CH_3	CHO	H	—	—	5.8 : 1	57
CH_3	CHO	H	200/2	88	1.8 : 1	73
CH_3	$COCH_3$	H	130/3	62	*	62
CH_3	$COCH_3$	H	200/5	81	2.3 : 1	109
CH_3	CN	H	200/2	89	2.2 : 1	73
CH_3	CO_2H	H	200/2	80	1.9 : 1	73
CH_3	CO_2CH_3	H	130/3	73	4.7 : 1	62
CH_3	CO_2CH_3	H	100/10	70	7.3 : 1	59
CH_3	CO_2CH_3	H	200/2	84	2 : 1	73
CH_3	CO_2CH_3	CH_3	220/2	70	9 : 1	59
CH_3	CO_2CH_3	CH_3	200/2	66	2.5 : 1	73
CH_3	$CO_2C_2H_5$	CH_3	200/12	95	1.4 : 1	72
CH_3	$CO_2C_2H_5$	C_2H_5	200/60	61	*	66
CH_3	$CO_2C_2H_5$	iso-C_3H_7	200/15	43	4.2 : 1	73
CH_3	C_6H_5	H	160/24	20	*	69
CH_3	C_6H_5	H	200/10	31	3.5 : 1	109
CH_3	NO_2	H	150/5	47	3.7 : 1	109
CH_3	phenylmaleic anhydride		80	74	12.4 : 1	76
C_2H_5	phenylmaleic anhydride		80	61	6 : 1	76
n-C_3H_7	CO_2CH_3	H	200/2	81	2.4 : 1	75
n-C_3H_7	CO_2CH_3	CH_3	200/2	65	3.4 : 1	75
iso-C_3H_7	CO_2CH_3	H	200/5	65	3 : 1	75
iso-C_3H_7	CO_2CH_3	CH_3	200/5	43	7.3 : 1	75
iso-C_3H_7	$CO_2C_2H_5$	iso-C_3H_7	200/10	31	14 : 1	75
iso-C_3H_7	phenylmaleic anhydride		80	59	8.6 : 1	76
t-C_4H_9	CO_2H	H	150/10	45	*	27
t-C_4H_9	CO_2CH_3	H	200/5	47	3.5 : 1	75
t-C_4H_9	CO_2CH_3	CH_3	200/5	36	10 : 1	75
iso-C_6H_{11}**	CO_2H	H	—	—	4 : 1	77
iso-C_6H_{11}	CHO	H	110/4	72	4 : 1	78
iso-C_6H_{11}	CHO	CH_3	160/6	73	4 : 1	78
C_6H_{11}	CN	H	135/18	90	4 : 1	78
C_6H_5	CO_2H	H	140	77	2.5 : 1	82
C_6H_5	COH_2	H	80	20	7 : 1	82
C_6H_5	CN	H	80/12	33	4 : 1	82
C_6H_5	CO_2CH_3	H	150/5	73	4.5 : 1	40
C_6H_5	CO_2CH_3	CH_3	150/5	51	14 : 1	40
Cl	CO_2H	H	150/5	85	9.3 : 1	94
Cl	C_6H_5	H	150/12	20	14 : 1	94
CH_3	CO_2H	H	150/10	72	8 : 1	94
CH_3O	C_6H_5	H	150/10	59	12 : 1	94

* Traces of the *meta*-isomer.

** $CH_2CH_2CH=C(CH_3)_2$

power: $Cl > CH_3O > C_6H_5 > CH_3$. Comparison of the condensation at 200° of isoprene with dienophiles of the type $CH_2 : CHX$ enables us to arrange the substituents according to their orienting power when present in the dienophile $NO_2 > C_6H_5 > COOH$, CH_3COO, CH_3CO, CN, CHO.

Comparison of Tables 1 and 3 reveals a more marked structural selectivity in the condensations of 1-substituted than in those of 2-substituted dienes. Thus a given substituent exerts a greater orienting power in the 1- than in the 2-position.

In condensations of 2-alkylbutadienes with unsymmetrical dienophiles, formation of the transition complex corresponding to the *meta*-adduct is sterically the more difficult[60,61]. If the steric factor is important, the amount of *meta*-isomer in the mixture of adducts should diminish with increasing bulk of the substituents in the dienophile and in the 2-position of the diene. This argument is fully supported by the data in Table 4, relating to the condensation of 2-alkylbutadienes with esters of 2-substituted acrylic acids.

According to modern views, diene synthesis takes place *via* a cyclic transition state which is stereochemically similar to the adduct, the diene and dienophile molecules arranging themselves in parallel planes[110-120]. On the

TABLE 4. Ratio of *para*-to *meta*-isomers in condensations of 2-alkylbutadienes (at 200°)[29].

Diene	Dienophile: H, $CH_2=C(H)COOCH_3$	Dienophile: CH_3, $CH_2=C(CH_3)COOCH_3$	Dienophile: $CH(CH_3)_2$, $CH_2=C(CH(CH_3)_2)COOC_2H_5$
$CH_2=C(CH_3)-CH=CH_2$	2 : 1	2.5 : 1	4.2 : 1
$CH_2=C(C_2H_7)-CH=CH_2$	2.4 : 1	3.4 : 1	—
$CH_2=C(CH(CH_3)_2)-CH=CH_2$	3 : 1	7.3 : 1	14 : 1
$CH_2=C(C(CH_3)_3)-CH=CH_2$	3.5 : 1	10 : 1	20 : 1

basis of this model of the transition state, rough estimates were made of the steric hindrance in diene synthesis as measured by the linear overlap of the van der Waals radii of the substituents in the diene and in the dienophile[61]. The results are compared in the diagram with experimental data on the relative proportions of the structural isomers (Tables 2 and 4).

The diagram shows very good agreement between the increase in steric hindrance to the formation of a structural isomer and the diminution in its content in the mixture of adducts. Thus steric effects are of great importance in diene condensations involving alkylbutadienes. Nevertheless, it must be noted that, in condensations of 1-alkylbutadienes with unsymmetrical dienophiles, the *ortho*-isomers predominate in the adduct mixtures, and steric hindrance must be overcome in their formation. Therefore the steric factor, in spite of the important part which it plays, cannot be regarded as paramount for structural directivity in diene synthesis.

Condensations of isoprene and of 2-isopropyl-, 2-t-butyl-, and 2-phenyl-butadiene[40,61,73] have been used as examples in studying the temperature dependence of structural directivity in the reactions of 2-substituted dienes.

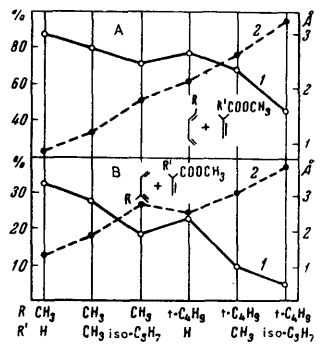
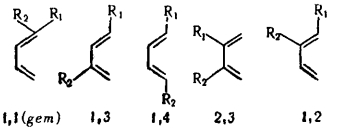


Fig. A: 1) % of *ortho*-isomer in mixture of adducts; 2) steric hindrance to the formation of the *ortho*-isomer.
Fig. B: 1) % of *meta*-isomer in mixture of adducts; 2) steric hindrance to the formation of the *meta*-isomer.

In all cases the amount of the *meta*-isomer was found to increase with rise in temperature: *i.e.* the composition of the adduct mixtures tended to even out, as with the 1-substituted dienes. Thus the following values were obtained for the *para* : *meta* ratio in the condensation of isoprene with methyl acrylate: 5.4 : 1 at 20°, 2.0 : 1 at 200°, and 1.4 : 1 at 400°.[73] This variation in composition of the adduct mixture with temperature can be explained (as with the condensations of penta-1,3-diene) by assuming that the activation energy of formation is about 1 kcal mole^{-1} smaller for the *para*- than for the *meta*-isomer[61].

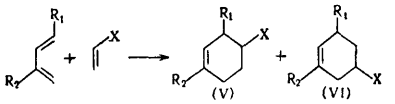
4. DISUBSTITUTED DIENES

Disubstituted dienes exist as five structural isomers, the arrangement of the substituents in which influences the structural orientation of diene synthesis in different ways.



Unfortunately, it is impossible to assess exactly the effect of geminal substitution on structural orientation, since *1,1-disubstituted dienes* undergo diene synthesis only after preliminary isomerisation into the 1,3-disubstituted dienes. Thus 1,1-dimethylbutadiene reacts with dienophiles only after isomerisation into 1,3-dimethylbutadiene, and 2,5-dimethylhexa-2,4-diene only after conversion to the corresponding 1,3-diene[121-123].

With *1,3-disubstituted dienes* each substituent may be expected to enhance the effect of the other, not to compete with it, since the substituent in the 1-position of the diene is *ortho*-directing, while that in the 2-position is *para*--directing. In fact, 1,3-dimethylbutadiene[12,17] and 1-methyl-3-isohexenylbutadiene[124-127] form only adducts of type (V) with acrylic acid and its derivatives:

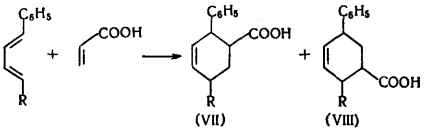


The same applies to the reactions of acrylic acid with 1-methyl-3-phenyl- and 3-methyl-1-phenyl-butadienes[128]. It is only quite recently that it has proved possible to isolate ~ 5% of isomer (VI) in the condensation of 1,3-dimethylbutadiene with methyl acrylate, methyl methacrylate, and acrylonitrile[129].

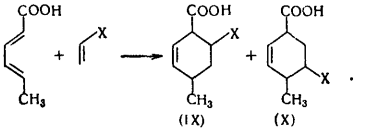
The study of structural orientation in the condensations of other types of disubstituted butadienes is of the greatest interest. The reactions of 1,4-disubstituted dienes with unsymmetrical dienophiles enable us to compare the orienting power of different substituents in the 1-position of the diene. Condensations of 2,3-disubstituted dienes make it possible to assess the orienting power of substituents in the 2-position. Finally, condensations of 1,2-disubstituted dienes permit comparison of the orienting power of substituents in the 1- and 2-positions of the diene.

Of course, when different substituents are present in the 1- and 4-positions of a diene, the adduct which is formed preferentially will be that in which the dienophile substituent is *ortho* to the most strongly orienting substituent in the diene§.

Condensation of 1-methyl-4-phenylbutadiene with acrylic acid[135] yielded adducts (VII) and (VIII) (R = CH_3) in the ratio 9 : 1, whereas reaction of 4-phenylbutadiene-1-carboxylic acid with acrylic acid[135] gave only adduct (VII) (R = COOH). Thus the phenyl group in the 1-position has a far stronger orienting effect than have methyl and carboxyl.



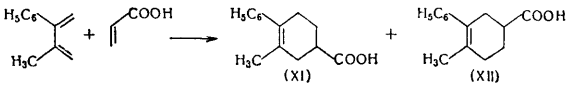
The orienting power of the methyl and carboxyl substituents can be compared by studying the diene condensations of sorbic acid:



Reaction of the chlorides and ethyl esters of sorbic and acrylic acids[136,137] yielded only the *ortho*-methyl isomer (X), whereas condensation with phenyl vinyl ketone resulted in the *ortho*-carboxy-isomer (IX)[138]. Alder *et al.*[135], who have studied this question most thoroughly, have shown that condensation of sorbic and acrylic acids produces a mixture of structural isomers with a slight preponderance of adduct (X). On the other hand, condensation with substituted styrenes[139], 1-vinylnaphthalene[53], indene[140], 1,2-dihydronaphthalene[140], and 1,2-dihydro-7-methoxynaphthalene[141] gave only adducts of type (IX) with *ortho*-orientation to the carboxyl. Reaction of methyl sorbate with styrene[123] yields a mixture of the two structural isomers, also with adduct (IX) preponderant.

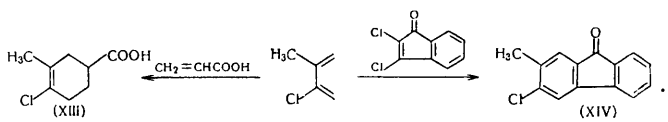
Thus adduct (X) predominates in the condensation of sorbic acid with acrylic acid, but adduct (IX) in its condensation with styrene. It is evident that methyl and carboxyl substituents in the diene are very similar in orienting power, and the nature of the substituent in the dienophile, which is in general less important, can substantially change the pattern of structural directivity.

Diene condensations of *2,3-disubstituted dienes* have been little studied. Reaction of 2-methyl-3-phenylbutadiene with acrylic and propiolic acids[142] gave a mixture of adducts with a slight preponderance of isomer (XI), in which phenyl exerts the main directing influence:



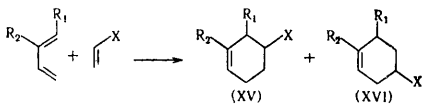
§ The data cited here relate solely to the *trans-trans*-isomers of 1,4-disubstituted dienes, since *cis-cis*-isomers of these dienes do not react at all by the mechanism of diene synthesis, while *cis--trans*-isomers either do not undergo reaction or else react with great difficulty[130-134].

Condensation of 2-chloro-3-methylbutadiene with acrylic acid[142] yielded almost exclusively adduct (XIII), in which the chlorine has determined the orientation. An analogous situation was observed in the reaction of this diene with dichloroindenone, which resulted in adduct (XIV)[143]. Thus chlorine exerts a far stronger orienting effect than does the methyl group:



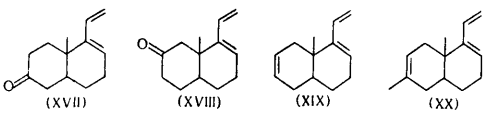
(XIII) (XIV)

In *1,2-disubstituted dienes* preferential orientation with respect to the substituent in the 1-position should lead to formation of adduct (XV), whereas the substituent in the 2-position will tend to favour formation of adduct (XVI). If the substituents R_1 and R_2 are identical, the latter, which is more remote from the reaction centre, has less influence on the orientation of the dienophile, as was to be expected. Thus condensation of 1,2-dimethylbutadiene with acrylonitrile and with methyl methacrylate[59] gives a (XV) : (XVI) ratio of about 6 : 1, whereas condensation of 1,2-diphenylbutadiene with acrylic acid[144] yields solely the isomer (XV).



(XV) (XVI)

1,2-Disubstituted dienes include also the vinylcycloalkenes in which the substituents R_1 and R_2 form part of a ring system. Only adducts of type (XV) could be isolated in most of the condensations which have been carried out with vinylcyclohexene[145-147], as well as in the dimerisation of styrene[148]. Condensation of the bicyclic dienes (XVII)–(XX) and of 1-vinylnaphthalene with citraconic anhydride and various cyclic ketones has been studied[53,149-154] in connection with the synthesis of polycyclic compounds related to the steroids, and here too only isomers of type (XV) were obtained. It was only in the condensation of vinylcyclohexene with acrylonitrile[59], propiolic acid[155], citraconic anhydride[156], and dimethyl mesaconate[157] that the (XVI) isomer could be isolated (5–15%) and its structure determined. Thus in cyclic dienes too a substituent in the 2-position of a diene system has a weaker orienting effect than a substituent in the 1-position.



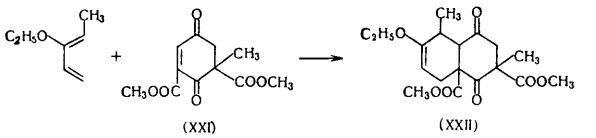
(XVII) (XVIII) (XIX) (XX)

Two possibilities arise if the substituents in positions 1 and 2 are different.

1. The substituent in position 1 is more strongly orienting than the substituent in position 2. In this case the structural directivity will be governed by the substituent in the 1-position, which should lead to exclusive formation of adducts of type (XV). In fact such adducts were alone obtained in the condensation with acrylic and propiolic acids of 1-phenylbutadienes substituted in the 2-position by methyl, ethyl, and methoxycarbonyl groups respectively[144].

2. The substituent in position 1 of the diene has a weaker orienting power than the substituent in position 2. In this case competition from the 2-substituent is quite strong, so that the reaction yields a mixture of the two isomers.

Thus in the condensation of 1-methyl-2-phenylbutadiene with acrylic acid[144] the ratio of (XV) to (XVI) is 4 : 1, and in the reaction of 2-chloro-1-ethyl(and methyl)butadienes with propiolic acid[158] the ratio is 3 : 1. A mixture of structural isomers, in which adducts of type (XV) usually slightly preponderate, is formed also in the condensation of 6-methoxy-1-vinyloctalin with citraconic anhydride and various cycloalkenones[159-165]. Condensation of 2-ethoxy-1-methylbutadiene with compound (XXI)¶ gives only adduct (XXII), in which the methoxycarbonyl is *para* to the ethoxy-group[166]. It is evident that, even in the 2-position, the ethoxy-group exerts a stronger orienting effect than the methyl group in the 1-position:

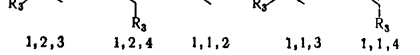


(XXI) (XXII)

Collation of the data for the condensation of 1,4-, 2,3-, and 1,2-disubstituted dienes enables us to derive the following sequence of substituents based on their orienting power when present in the diene: Cl, RO, C_6H_5 > COOH > > CH_3. Comparison with the data in Sections 2 and 3 makes it obvious that the sequence of substituents according to their orienting power in the diene is roughly the same for mono- and di-substituted dienes.

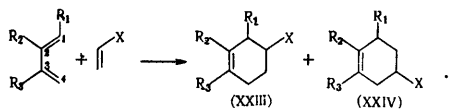
5. TRISUBSTITUTED DIENES

Three substituents in a diene molecule can be arranged in five different ways, resulting in the existence of five structural isomers:



1,2,3 1,2,4 1,1,2 1,1,3 1,1,4

Data on the structural directivity of diene synthesis with disubstituted dienes can serve as a basis for explaining the structure of adducts obtained in the condensation of more highly substituted dienes. An example is provided by the condensation of *1,2,3-trisubstituted dienes*, in which two adducts, (XXIII) and (XXIV), can be formed, with the dienophile substituent oriented *ortho* to positions 1 or 4 of the diene system:



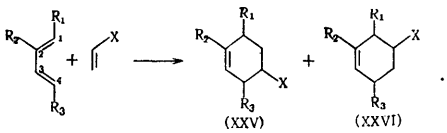
(XXIII) (XXIV)

The substituent from the dienophile will be directed to the 1-position (isomer XXIII) by substituents R_1 and R_3, and to the 4-position (isomer XXIV) only by substituent R_2. Since substituents in a diene system are considerably less strongly orienting when in positions 2 and 3 than in 1 and 4, almost exclusive formation of the (XXIII) isomer can be expected in condensations of 1,2,3-trisubstituted dienes.

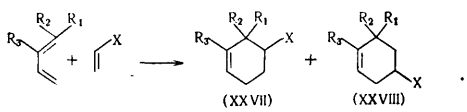
¶ A mixture of the two structural isomers is obtained also in the condensation of this diene with toluquinone[167].

This conclusion has been confirmed in a study of the condensation of 1,2,3-trimethylbutadiene with acrylonitrile and with crotonaldehyde: in neither case did the content of the (XXIV) isomer exceed 5–7% of the mixture of adducts[168]. An analogous pattern should obviously be observed in condensations involving cyclic dienes having this type of substitution. The reactions of 1-isopropenylcyclohexene with citraconic anhydride[169] and of 1-α-acetoxyvinylcyclohexene with derivatives of acrylic acid, with citraconic anhydride, and with 2,6-xyloquinone[170-176] did actually result exclusively in (XXIII) adducts with "contiguous" substituents. Dimerisation of atropic acid[177] and its nitrile[178] also yields adducts of type (XXIII).

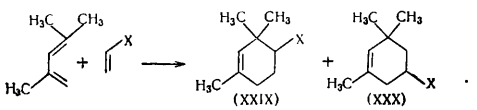
In the reactions of *1,2,4-trisubstituted dienes* the dienophile substituent is directed to the 4-position of the diene system (adduct XXV) by substituents R_2 and R_3, and to the 1-position (adduct XXVI) only by R_1. Hence preferential formation of the first isomer is to be expected, as has been confirmed in a study of the condensation of alloocimene[179] and of 1-β-acetoxyvinylcyclohexene[180,181] with acrylic acid and its derivatives:



1,1,2-Trisubstituted dienes undergo only partial diene synthesis without isomerisation into 2-substituted and 1,2,3-trisubstituted[168,182] dienes. The simplest representative of this group — 1,1,2-trimethylbutadiene — forms adducts of type (XXVII) in diene condensations with unsymmetrical dienophiles[121,123,168]. Similar structural directivity was shown in the condensation of 2-isopropyl-1,1-dimethylbutadiene with acrylonitrile[182]. In several papers, however, adducts of 1,1,2-trimethylbutadiene with crotonaldehyde and but-2-ynal have been assigned structure (XXVIII)[183-188]:



1,1,3-Trisubstituted dienes have been studied only in the case of the diene condensations of 1,1,3-trimethylbutadiene, which undergoes diene synthesis without isomerisation, since migration of the double bonds along the carbon skeleton does not change the substitution pattern[123]. All three substituents in dienes of this type orient the dienophile in the same direction, and therefore almost exclusive formation of adducts of type (XXIX) is to be expected from their condensations.

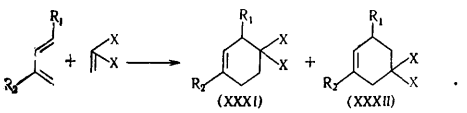


And indeed 1,1,3-trimethylbutadiene does form adducts of type (XXIX) with acrolein[189,190], crotonaldehyde[191], but-2-ynal[192], hept-2-ynal[192], acrylic acid[12], and propiolic[193] and methylenemalonic[194] esters. Adduct (XXX) could be isolated only from the condensation of this diene with acrylonitrile[195], and then in amount not exceeding 3–5% of the adduct mixture.

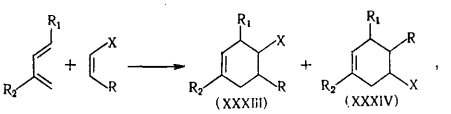
The structural directivity in the condensation of *1,1,4-trisubstituted dienes* has not been investigated, although it has been shown that 1,1,4-trimethylbutadiene can undergo partial diene synthesis without isomerisation[122].

6. DISUBSTITUTED DIENOPHILES

Only a very small number of 1,1-disubstituted dienophiles have been studied†. Thus condensation of diethyl methylenemalonate with isoprene[194], 2-phenylbutadiene[196], and penta-1,3-diene[16,194] produces only the (XXXI) isomer (where X = C_2H_5COO). The same isomer (X = CN) is formed also in the reaction of 2-phenylbutadiene with the corresponding dinitrile (vinylidene dicyanide)[197]. Thus the reactions of 1,1-disubstituted dienophiles are quite analogous to those of monosubstituted dienophiles both with 1-substituted and with 2-substituted dienes.



The condensations of *1,2-disubstituted dienophiles* with unsymmetrical dienes enable us to study the orienting effects of different substituents in the dienophile. The weakest orienting effect in the dienophile is evidently exerted by an alkyl substituent. Thus the condensation of isoprene[112], penta-1,3-diene[12,59], and vinylcyclohexene[146] with crotonic acid results in mixtures of adducts having a marked preponderance of the (XXXIII) isomer, in which the carboxyl exerts the main orienting influence:



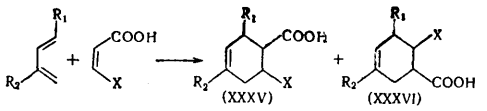
where X = COOH, CHO, NO_2, C_6H_5; R = CH_3, C_2H_5, C_3H_7.

The same isomer is formed in the reaction of 2-ethoxybutadiene with 3-ethylacrylic acid[83], and also in the condensation of penta-1,3-diene[21], 2-ethoxybutadiene[198], and vinylcyclohexene[155] with but-2-ynoic acid. The condensation of penta-1,3-diene[17,191] and 2-isopropylbutadiene[168] with crotonaldehyde and that of isoprene[199], 2-methoxybutadiene[95,103,104], and vinylcyclohexene[200,201] with unsaturated cyclic ketones also give adducts of type (XXXIII). Finally, this adduct (X = NO_2) is formed in the condensation of penta-1,3-diene with nitropentene[202]. Thus the carboxyl, carbonyl, and nitro groups are more strongly orienting than are alkyl groups in the dienophile. No data are available for a direct comparison of the orienting effects of phenyl and alkyl groups, but in view of the fact that the condensation of indene with isoprene gives predominantly, and that with penta-1,3-diene solely, adducts of type (XXXIII)[203], it can be concluded that phenyl also is more strongly orienting than are alkyl groups.

Several instances are available for comparing the orienting effect of the carboxyl group with those of other groups.

† The effect of an alkyl group in the 1-position of a dienophile has been considered above in discussing the role of the steric factor in structural directivity.

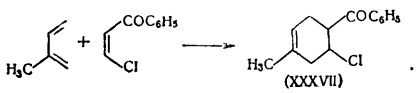
Condensation of isoprene and of 1-phenylbutadiene with 4,4,4-trifluorocrotonic acid[204] results in the formation of adducts of type (XXXV) with orientation with respect to the carboxyl group.



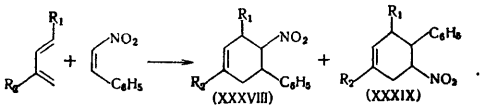
where X = CF_3, C_6H_5, CH_3CO.

This type of isomer is the main product in the reaction of various dienes with cinnamic acid[128,205-207] and its analogues — 2,6-dimethoxy-4-n-pentylcinnamic[208] and *o*-nitrocinnamic[209] acids — and also with phenylpropiolic acid[21], cinnamaldehyde[206], and methyl styryl ketone[207]. Nevertheless, the condensation of 3-acetylacrylic acid with 2-phenylbutadiene[83], 2-*p*-methoxyphenylbutadiene[210], and 1-vinylnaphthalene[159] resulted in mixtures of isomers consisting mainly of the (XXXVI) adduct. Hence it can be concluded that the carboxyl group is more strongly orienting than trifluoromethyl and phenyl in the dienophile, but less strongly orienting than the acetyl group.

Diene condensation of isoprene with 2-chlorovinyl phenyl ketone[211] yields adduct (XXXVII), and therefore the keto--group is more strongly orienting than chlorine:



Finally, the phenyl and nitro groups can be compared by examining the condensation of unsymmetrical dienes with β-nitrostyrene‡. Condensation of isoprene, penta-1,3--diene, and 2-ethoxybutadiene with this dienophile results in the formation of mixtures of adducts containing mainly the (XXXVIII) isomer, in which orientation is determined chiefly by the nitro-group[202,212]. The corresponding isomer was obtained in the condensation of isoprene with 4-methoxy-β-nitrostyrene[69] and of 2-ethoxybutadiene with 2,4-dimethoxy-β-nitrostyrene[69].

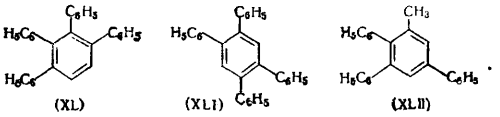


Published data enable us to arrange substituents in the following sequences according to their orienting power in a dienophile: COR, NO_2 > COOH > CF_3, C_6H_5 > CH_3; COR > Cl. These series are derived from a study of disubstituted dienophiles, in which the substituents act on one another through the double bond. The structural directivity is then characteristic not so much of the sum of or the difference between the effects of the individual substituents as of the molecule as a whole. Discrepancies can therefore arise in deductions made from studies of monosubstituted and of disubstituted dienophiles. Thus whereas in monosubstituted dienophiles phenyl proves to have a stronger orienting effect than carboxyl (see Sections 2 and 3), in the disubstituted dienophile containing both of these groups (cinnamic acid) it is the carboxyl which, in contrast, exerts the main orienting effect.

‡ Product orientation in the condensation of isoprene with 1--nitro-3,3,3-trichloropropene has also been studied,[213] but the proportions of the resulting structural isomers were not determined.

7. CYCLIC DIENES

In comparison with acyclic dienes, those compounds in which the two double bonds are located in the same ring exhibit several peculiarities with respect to structural directivity. We can take as an example the condensations undergone by substituted cyclopentadienones. Whereas the reactions of 1,2,3- and 1,2,4-triphenylcyclopentadienones with phenylacetylene[214] result in the formation of adducts (XL) and (XLI) in conformity with the rules of orientation derived above for trisubstituted acyclic dienes, the condensation of 1-methyl-2,3-diphenylcyclopentadienone with this dienophile[215] apparently gives adduct (XLII), in violation of these rules.



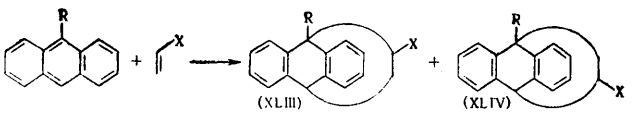
Structural directivity is almost completely absent in the condensation of 1,5,5-trimethylcyclopentadiene[216] and of 2,6,6-trimethylcyclohexa-2,4-dienone[217] with vinyl acetate, for the two structural isomers are formed in about equal amounts.

An especially thorough study has been made of structural directivity in the condensations undergone by 9-substituted anthracenes. Since these compounds are formally analogous to 1-substituted butadienes, their reactions with unsymmetrical dienophiles can lead to the formation of isomers having *"ortho"* (XLIII) or *"meta"* (XLIV) orientation. The results obtained were quite unexpected. It was found that completely different ratios of the structural isomers could be obtained even when the substituents in the reactants had very similar electronic and steric characteristics. The data in Table 5 show that these ratios vary from exclusive

TABLE 5. Condensation of 9-substituted anthracenes with unsymmetrical dienophiles.

Diene R	Dienophile X	Reaction conditions, *t*, °C/h	Yield of adducts, %	Ratio (XLIII)/(XLIV)	References
CN	COOH	140/2	21	(XLIII) alone	218
CN	$COOCH_3$	140/21	38	ditto	218
CN	$CONH_2$	130/16	25	»	218
CHO	COOH	130/24	62	»	219
CHO	CN	130/24	78	»	219
CHO	CH_2OH	200/12	63	»	219
$CH(OCH_3)_2$	$COOCH_3$	120/17	60	2.8 : 1	220
CN	CH_2OH	175/16	50	2.1 : 1	220
$CONH_2$	COOH	125/3	20	2 : 1	221
$CONH_2$	CH_2OH	170/17	62	2 : 1	221
NO_2	$CONH_2$	160/48	39	1.7 : 1	221
NO_2	CN	135/24	—	1.3 : 1	221
NO_2	COOH	150/20	93	(XLIII) < (XLIV)	221
CN	CN	200/22	51	1 : 1.8	218
NO_2	COCl	135/24	78	1 : 5.5	221
COOH	COOH	150/9	20	(XLIV) alone	54
COO	COO	230/36	75	ditto	54
NO_2	$COOCH_3$	135/24	60	»	221
NO_2	CH_2OH	190/20	6	»	221

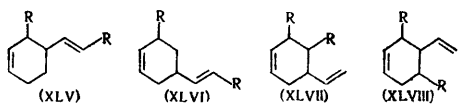
formation of the *ortho*-isomer (XLIII) to complete predominance of the *meta*-isomer (XLIV). This phenomenon has not yet been satisfactorily explained, and is at variance with all other data on structural directivity.



The comparatively few data available on structural directivity in condensations of cyclic dienes do not permit any generalisations to be made. The results which have been obtained clearly make it necessary to approach cautiously the question of extending to cyclic compounds the conclusions reached with acyclic dienes.

8. DIMERISATION OF MONOSUBSTITUTED DIENES

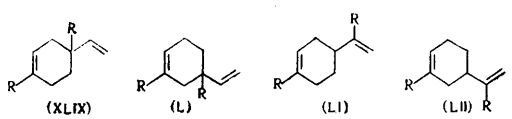
The dimerisation of diene compounds with formation of a six-membered ring is considered as a particular case of diene synthesis. It must be borne in mind that dimers containing four- and eight-membered rings can also be formed[222-225]. A brief account will be given in the present section of the most important work on the dependence of product orientation on structure in the dimerisation of monosubstituted dienes.



In most work on the dimerisation of *1-substituted dienes*, of the four theoretically possible structural isomers (XLV)–(XLVIII) containing a six-membered ring, only the dimer (XLV), resulting from the reaction at the unsubstituted vinyl group of the diene, could be obtained.

Thus this type of isomer has been obtained in the dimerisation of 1-phenylbutadiene[226], 1-cyanobutadiene[227,228], butadiene-1-carboxylic acid[229], and hexa-1,3,5-triene[230]. It was shown[231] in 1955, however, that the dimerisation of penta-1,3-diene at 140°–240° yields, practically independently of the temperature, a mixture of dimers containing about 90% of (XLV), 4–5% of (XLVI), and 1–2% each of (XLVII) and (XLVIII). Thus in this case all the possible structural isomers could be isolated, the ratio of *ortho*- to *meta*-dimers being about 13 : 1.

The dimerisation of *2-substituted dienes* also can result in four isomers, (XLIX)–(LII), containing a six-membered ring. For a long time it was assumed that only the *para*-dimers (XLIX) and (LI) were formed in the reaction.

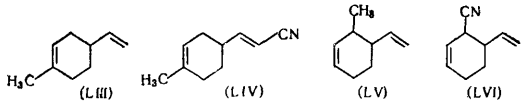


This conclusion was based on a study of the dimerisation of 2-methoxy- and 2-formyloxy-butadienes [dimer (LI) was isolated][232], 2-neopentylbutadiene (LI)[233], chloroprene [(XLIX) and (LI)][234], 2-phenylbutadiene [(XLIX) and (LI)][81,235], 2-cyanobutadiene (XLIX)[236,237], and butadiene-2-carboxylic acid (XLIX)[238]. Nevertheless, it was believed that isoprene forms a mixture of *para*- and *meta*-dimers in which the *meta*-isomer predominates in some cases[239-242]. It is interesting that only the *meta*-dimer of type (L) was isolated also in the dimerisation of isopropenylacetylene [2-methylbut-1-en-3-yne][243].

These views have been substantially amended recently. Thus in the dimerisation of isoprene (at 100°–300°) it has proved possible to isolate all the theoretically possible dimers, rise in temperature being found to increase the content of dimers (XLIX) and (LI) and decrease that of (L) and (LII) in the mixture. The *meta*-isomer (L) predominated in the first fraction at low temperatures, and the *para*-isomer (XLIX) at high temperatures[244,245]. The preferential formation of *meta*-dimers and the reversal of structural directivity with rise in temperature distinguish the dimerisation of isoprene from that of all other dienes. This difference may be associated with peculiarities in the mechanism of the dimerisation of isoprene[246].

The dimerisation of chloroprene at 20°[247] resulted in the formation of roughly equal fractions comprising dimers (LI) + (LII) and (XLIX) + (L) respectively. The *para*-dimer (XLIX) predominated in the latter, and the *meta*-dimer (LII) in the former. In contrast to the low-temperature dimerisation of isoprene, the total content of the *meta*-isomer in the mixture of dimers did not exceed one-third.

In reactions between two different dienes it has proved possible in some cases to determine the structure of the compounds which are formed preferentially. Thus the reaction of isoprene with butadiene[248,249] and with 1-cyanobutadiene[250] yielded mixtures of reaction products in which (LIII) and (LIV) respectively, with *para*-orientation of the substituents, were the main products. The reaction of penta-1,3-diene[249] and of 1-cyanobutadiene[251] with butadiene resulted mainly in the formation of isomers (LV) and (LVI), with *ortho*-orientation of the substituents. It is interesting that butadiene is in both cases involved in the reaction principally as the dienophile.

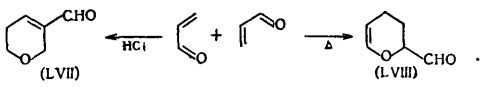


Thus structural directivity in the dimerisation of diene compounds follows basically the same rules as in other diene condensations in which they are involved. Dimerisation of 1-substituted dienes yields mainly *ortho*-dimers, whereas that of 2-substituted dienes gives the *para*-dimers. The behaviour of isoprene (and to a less extent of chloroprene), however, differs markedly from that of the other dienes whose dimerisation has been investigated.

9. DIENES AND DIENOPHILES CONTAINING HETEROATOMS

Besides the "classic" diene synthesis, *i.e.* the condensation of dienes and dienophiles having double bonds between carbon atoms, the formation of six-membered heterocycles from unsaturated compounds containing heteroatoms is also often included in this group of reactions (see Hahn's review[252]). At the present time there is no generally accepted view as to how closely the mechanism of such heterocyclisation reactions approaches that of the "classic"

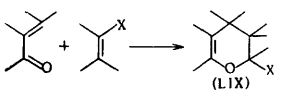
diene synthesis. Condensations involving compounds containing the strongly polar C=O, C=N, C≡N, or N=O bonds could be reasonably regarded as taking place by an ionic mechanism. But evidently this is not so. In the dimerisation of acrolein under the influence of traces of hydrochloric acid, for example, which undoubtedly takes place by an ionic mechanism, dimer (LVII) is formed; nevertheless, thermal reaction yields dimer (LVIII)[253]. The thermal cleavage of dihydropyran at 540° into ethylene and acrolein is a homogeneous reaction which is completely analogous to the retrodiene decomposition of cyclohexene into ethylene and butadiene[254].



(LVII) (LVIII)

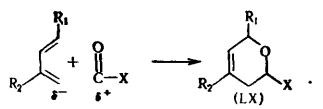
This all suggests that the mechanism of such thermal reactions is similar to that of diene synthesis. We must therefore examine the main results obtained on structural directivity in this field.

Study of the reactions of unsaturated aldehydes and ketones with unsymmetrical dienophiles shows that, when either electron-donor or electron-acceptor substituents are present in the dienophile, only adducts of type (LIX) are formed[210,255-257]. Compounds of the same type have been obtained by the dimerisation of unsaturated aldehydes and ketones[258,259]:

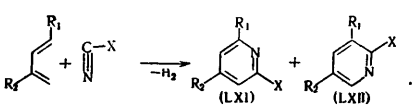

(LIX)

where X = OR, SR, CH_3COO, COR, COOR, CN, CH_2OH, C_6H_5, and C_1-C_6 alkyl.

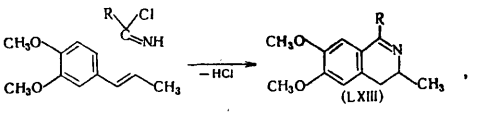
Structural directivity in the condensation of dienes with aldehydes was studied in the reactions of isoprene with chloral[260] and of 1,3-dimethylbutadiene with formaldehyde[261]. It was proved in both cases that adducts of type (LX) were formed with orientation according to the polarity of the reactant molecules:


(LX)

The structure of the adducts was established also in the condensation of unsymmetrical dienes with cyanogen[262], acetonitrile[263], and benzonitrile[264], which were accompanied by dehydrogenation of the adducts to pyridine derivatives. The reactions involving isoprene and 1,3-dimethylbutadiene resulted in the (LXI) isomer; but the condensation of chloroprene with cyanogen produced a mixture of adducts in which the other isomer [(LXII), with X = CN] predominated:


(LXI) (LXII)

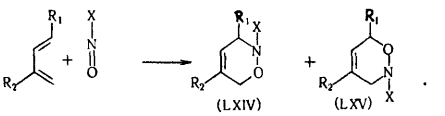
Condensation of isosafrole and methylisoeugenol with imino-chlorides gives adducts of type (LXIII)[265,266]:



(LXIII)

where R = H, CH_3, C_6H_5.

Reaction of dienes with nitroso-compounds can give adducts (LXIV) and (LXV). With adducts of chloroprene where X = cyclohexyl and 1-cyanocyclohexyl[267,268], and also with adducts of penta-1,3-diene in which X = C_6H_5,[269] the (LXIV) isomer has been shown to predominate in the mixture. Since in the N=O bond the oxygen atom is negatively charged, structural isomers of type (LXIV) are formed in these cases in opposition to the polarity of the reactants:


(LXIV) (LXV)

The above results lead to the conclusion that, in diene condensations involving heterodienes and heterodienophiles, the orientation is independent of the polarity of either the diene or the dienophile component.

10. STRUCTURAL DIRECTIVITY AND MECHANISM OF DIENE SYNTHESIS

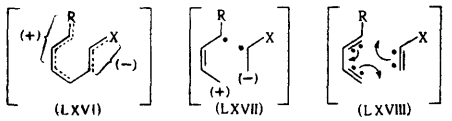
The mechanism of diene synthesis was recently reviewed by Syrkin and Moiseev[270], so that we need not discuss here the immense literature on this problem, but can confine ourselves to an examination, on the basis of the different reaction mechanisms, of the rules of structural directivity in this reaction.

The mechanisms which have been suggested for diene synthesis can be divided into two large groups — heterolytic and homolytic — according to the type of transition states which are postulated. The factors which influence structural directivity are governed primarily by the type of electron transfer, and are relatively independent of whether the reaction takes place in two stages, with the intermediate formation of kinetically independent reactive species, or in one stage *via* a cyclic transition complex. We can therefore consider one-stage and two-stage reaction mechanisms together.

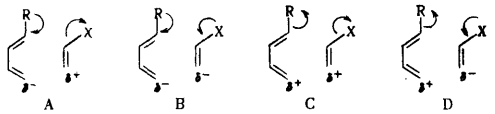
A special position is occupied by the proposed mechanism of diene synthesis which postulates complete delocalisation of electrons in the intermediate complex[270,271]. However, this mechanism explains structural directivity by the preferential orientation of diene and dienophile according to their polarity, *i.e.* in a manner analogous to a heterolytic mechanism, and therefore it will not be considered separately.

From 1932 onwards[272] several versions of a *heterolytic mechanism* of diene synthesis were put forward. It was assumed in most cases that the diene, as a nucleophilic reagent, attacks the double bond of the dienophile to form an intermediate ion (LXVI), which is then cyclised to the final reaction product[273-278]. Another view[279,280] was that

both diene and dienophile are converted before the reaction to dipolar ions, which react by a quadrupole mechanism to form the adduct. Woodward's scheme[118,119], according to which reaction takes place *via* the intermediate formation of a radical-ion complex (LXVII), linked by ionic forces, can also be regarded as a variant of an ionic mechanism. Finally, heterolytic displacement of electrons takes place also in "cyclic electron transfer" (LXVIII), which has recently been suggested as the mechanism of diene synthesis[281].



According to all these versions, structural directivity is governed by the presence in diene and dienophile molecules of fractional charges arising under the influence of substituents. Diene and dienophile molecules of different polarity can theoretically be combined in four ways (A–D), which are illustrated for the case of 1-substituted dienes:



It is obvious that, if the mode of reaction is determined by the polarity of the reactants, the *ortho–para*-isomers should be obtained preferentially in cases A and D (with opposite polarities of diene and dienophile), whereas the *meta*-isomers should predominate in cases B and C, with the reactants of like polarity. Examination of the literature for Sections 2 and 3 shows that most of the diene condensations which have been studied relate to case A, with an electron-donor substituent in the diene and an electron-acceptor substituent in the dienophile. In condensations of this type the structural directivity agrees with the polarity of the reactants, and this was previously regarded as providing confirmation of a heterolytic mechanism. However, quite a large number of diene condensations are now known in which formation of the adduct takes place in opposition to the polarity of the reactants. In addition to the condensations of heterodienes and heterodienophiles discussed in Section 9, the following reactions can be noted, in which *ortho–para*-isomers are formed instead of the *meta*-isomers (see Sections 2 and 3).

Reactions of type B (electron-donor substituents in diene and dienophile) include the condensations of penta-1,3-diene, isoprene, 1- and 2-phenylbutadienes, and 2-methoxybutadiene with styrene, of myrcene with vinyl acetate, and of 2-phenylbutadiene with phenylacetylene.

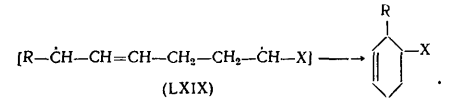
Reactions of type C (electron-acceptor substituents in diene and dienophile) include as examples the condensation of 1-*p*-nitrophenylbutadiene, 1-*p*-bromophenylbutadiene, 1-*o*-nitrophenylbutadiene, and butadiene-1-carboxylic acid with acrylic acid, of 1-cyanobutadiene with methyl acrylate, and of 2-cyanobutadiene with acrylonitrile and methyl vinyl ketone.

The formation of *ortho*-isomers in type C reactions of 1-substituted dienes has been explained[270] by deactivation of the double bond directly adjacent to the substituent in the diene. This makes the terminal C=C bond more reactive, and the reaction leading to the *ortho*-isomer becomes more advantageous. However, these ideas are obviously inapplicable to type C reactions of 2-substituted dienes and to all type B condensations, so that they are unable to explain deviations from the polar reaction scheme. It must therefore be concluded that *the polarity of the reactant molecules is not the decisive factor in the structural directivity of diene synthesis*.

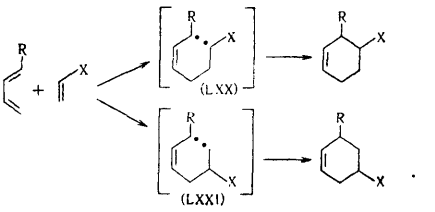
With this fact established we can discuss also the part played in structural directivity by "prereaction" interaction between the reactants. In many cases the diene synthesis is known to be preceded by the formation of a "prereaction" molecular complex between diene and dienophile[282,283]. Such complexes arise as a result of donor–acceptor interaction between the molecules[245], their formation involving unactivated molecules, which will doubtless be oriented in conformity with their polarity in the ground state. Since the structural directivity of diene synthesis does not conform with the polarity of the reactants, it cannot be determined by the orientation of the molecules in the "prereaction" molecular complex.

Thus a heterolytic mechanism cannot explain the structural directivity of diene synthesis. This conclusion, as well as kinetic[275] and energetic[270] data, shows that diene synthesis cannot take place *via* the formation of ionic intermediate states: the reaction is primarily, although not entirely, a homolytic process.

Most variants of the *homolytic mechanism* suggest that reaction takes place in one stage and that the transition state is an open-chain biradical (LXIX)[246,259,284,285]. Another view[286] is that diene synthesis takes place in two stages — formation of a biradical (LXIX) and its cyclisation to the end-product with a low activation energy. A "latent-radical" reaction mechanism has also been suggested, which presupposes homolytic displacement of electrons within a cyclic transition complex[61,287]:



A homolytic mechanism shows better agreement with the experimental data on structural directivity than does a heterolytic mechanism, since a characteristic feature of radical processes is that the mode of the reaction is practically independent of the polarity of the reactants. According to modern views, radical reactions involve the intermediate formation of the most stable radicals[288,289], tertiary radicals being more stable than secondary, and the latter in turn more stable than primary radicals. An explanation of the structural directivity of diene synthesis has been suggested on the basis of this principle[257,290]. Thus in the condensation of a 1-substituted diene with an unsymmetrical dienophile, the *ortho*-isomer is formed *via* a bisecondary biradical (LXX), whereas the *meta*-isomer involves a primary–secondary biradical (LXXI).



Since on the above basis radical (LXX) is more stable than (LXXI), the main product should be the *ortho*-isomer

regardless of the polarity of the substituents, as is actually observed. In the condensations of 2-substituted dienes, however, both structural isomers are formed *via* primary–secondary biradicals, and arbitrary assumptions must be made in order to explain the structural directivity; the same applies to condensations of disubstituted dienes and dienophiles.

Apart from this purely qualitative treatment, the concept of radical attack at the atom having the greatest free valence number, which has proved valuable with radical reactions in the aromatic series[291,292], can also be used in explaining the structural directivity of diene synthesis. Existing calculations[293] indicate that with styrene 2-vinylbutadiene should form mainly the *para*-isomer, whereas hexatriene with styrene should yield mainly the *meta*-isomer. This obviously contradicts experimental data on structural directivity. Thus a detailed interpretation of the effect of substituents on the proportions of structural isomers which is based on a radical mechanism encounters great obstacles, caused mainly by our inadequate knowledge of the relative stabilities of radicals. Nevertheless, the fundamental compatibility of a homolytic reaction mechanism with structural directivity is of very great significance.

The experimental study of structural directivity in diene synthesis has already reached a level which permits the investigator to foretell accurately, on the basis of empirical rules, which structural isomer will be the main product of a given reaction. The theoretical interpretation of the phenomena of structural directivity, however, lags far behind the accumulated experimental results. As follows from the above account, the structural directivity of diene synthesis has not yet found a comprehensive explanation on the basis of any particular reaction mechanism. Progress in this direction will evidently be associated primarily with the development of ideas on the mechanism of diene synthesis, which is a very peculiar reaction, combining features of both ionic and radical processes.

1. K. Alder, "Neuere Methoden der präparativen organischen Chemie", Vol.1, Berlin, 1943, p.257.
2. A. Norton, Chem. Rev., 31, 319 (1942).
3. H.L. Holmes, "Organic Reactions" (Translated into Russian), Vol.4, Inostr. Lit., 1951, p.86.
4. K. Alder, "XVI Congrès International de Chimie Pure et Appliquée", Basel–Stuttgart, 1955, p.86.
5. K. Alder and M. Schumacher, Annalen., 571, 108 (1951).
6. K. Alder and B. Krüger, Chem. Ber., 86, 985 (1953).
7. O. Grummitt and F. Christoph, J. Amer. Chem. Soc., 71, 4157 (1949).
8. O. Grummitt and F. Christoph, J. Amer. Chem. Soc., 73, 3479 (1951).
9. A.S. Onishchenko and N.I. Aronova, Dokl. Akad. Nauk SSSR, 132, 138 (1960).
10. H. Snyder, I. Stewart, and R. Meyers, J. Amer. Chem. Soc., 71, 1055 (1949).
11. D. Graig, J. Amer. Chem. Soc., 72, 1678 (1950).
12. K. Alder and W. Vogt, Annalen., 564, 120 (1949).
13. N.P. Sopov, Zhur. Obshch. Khim., 25, 2082 (1955).
14. W.A. Ayer, L.G. Humber, and W.I. Taylor, J. Chem. Soc., 3505 (1954).
15. J.S. Meek and J.W. Ragsdale, J. Amer. Chem. Soc., 70, 2502 (1948).
16. B.A. Arbuzov and E.G. Kataev, Zhur. Obshch. Khim., 20, 68 (1950).
17. H.L. Holmes, K. Alcock, D.G. Demianiw, J.W. Robinson, C.E.S. Rooney, and F.A. Sundberg, Canad. J. Res., 26B, 248 (1948).
18. W.Y. Huang, H.L. Holmes, and L.F. Fieser, J. Amer. Chem. Soc., 74, 5920 (1952).
19. A.A. Petrov and N.P. Sopov, Zhur. Obshch. Khim., 22, 591 (1952).
20. A.A. Petrov, Zhur. Obshch. Khim., 18, 1125 (1948).
21. E.G. Kataev and M.E. Mat'kova, Uch. Zap. Kazan. Univ., 115, No.3, 21 (1955).
22. A.A. Petrov and K.B. Rall', Zhur. Obshch. Khim., 26, 1588 (1956).
23. A.A. Petrov and N.P. Sopov, Zhur. Obshch. Khim., 25, 517 (1955).
24. A.A. Petrov and N.P. Sopov, Zhur. Obshch. Khim., 22, 890 (1952).
25. M. Tishler, L.F. Fieser, and N.L. Wendler, J. Amer. Chem. Soc., 62, 2870 (1940).
26. R.L. Frank, R.D. Emmick, and R.S. Johnson, J. Amer. Chem. Soc., 69, 2313 (1947).
27. K. Alder, K. Heimbach, and E. Kühle., Chem. Ber., 86, 1364 (1953).
28. I.N. Nazarov, Yu.A. Titov, and A.I. Kuznetsova, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 887 (1960).
29. I.N. Nazarov, Yu.A. Titov, and A.I. Kuznetsova, Dokl. Akad. Nauk SSSR, 124, 586 (1959).
30. E. Lehmann and W. Paasche, Chem. Ber., 68, 1146 (1935).
31. J.S. Meek, F.J. Lorenzi, and S.J. Cristol, J. Amer. Chem. c., Soc., 71, 1830 (1949).
32. K. Alder, H. Vogt, and W. Vogt, Annalen., 565, 135 (1949).
33. G. Blumenfeld, Ber., 74, 524 (1941).
34. G.A. Ropp and E.C. Coyner, J. Amer. Chem. Soc., 71, 1832 (1949).
35. J.S. Meek, B.T. Poon, R.T. Merrows, and S.J. Cristol, J. Amer. Chem. Soc., 74, 2669 (1952).
36. L. Reich and E.J. Becker, J. Amer. Chem. Soc., 71, 1834 (1949).
37. K. Alder, J. Haydn, and B. Krüger, Chem. Ber., 86, 1372 (1953).
38. J.W. Cook and C.L. Hewett, J. Chem. Soc., 62 (1936).
39. H.E. Zimmermann, J. Amer. Chem. Soc., 79, 6554 (1957).
40. I.N. Nazarov, Yu.A. Titov, and A.I. Kuznetsova, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 1270 (1959).
41. G.A. Ropp and E.C. Coyner, J. Amer. Chem. Soc., 72, 3960 (1950).
42. E.G. Kataev, Soobshch. Nauch. Rabot. Chlenov Vses. Khim. Obshch im. Mendeleeva, 2, 49 (1955).
43. E.A. Braude and J.S. Fawcett, J. Chem. Soc., 3113 (1951).
44. K. Alder and M. Schumacher, Annalen., 565, 148 (1949).
45. O. Wichterle and M. Hudlicky, Coll. Czech. Chem. Comm., 12, 564 (1947).
46. H.H. Inhoffen, H. Mixfeldt, H. Schaefer, and H. Krämer, Croat. Chem. Acta., 29, 329 (1957).
47. V.F. Kucherov, N.Ya. Grigor'eva, and I.N. Nazarov, Zhur. Obshch. Khim., 29, 793 (1959).
48. M.L. Stein and G. Casini, Gazzetta., 85, 1411 (1955).
49. W. Langenbeck, O. Gödde, L. Weschky, and R. Schaller, Ber., 75, 232 (1942).
50. S. Hünig and H. Kahanek, Chem. Ber., 90, 238 (1957).
51. H.R. Snyder and G.I. Poos, J. Amer. Chem. Soc., 72, 4104 (1950).
52. K. Alder, M. Schumacher, and O. Wolff, Annalen., 564, 79 (1949).
53. W.E. Bachmann and N.C. Deno, J. Amer. Chem. Soc., 71, 3062 (1949).
54. K. Alder and K. Heimbach, Chem. Ber., 86, 1312 (1953).

55. Yu.A.Titov and A.I.Kuznetsova, Dokl.Akad.Nauk SSSR, 126, 586 (1959).
56. Yu.A.Titov and A.I.Kuznetsova, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk., 1817 (1960).
57. A.A.Petrov and N.P.Sopov, Zhur.Obshch.Khim., 27, 1795 (1957).
58. V.J.Richter, "Chemistry of Petroleum Hydrocarbons", Reinhold Publ.Corp., New York, 1954, Vol.1, p.568.
59. I.N.Nazarov, A.I.Kuznetsova, and N.V.Kuznetsov, Zhur. Obshch.Khim., 25, 88 (1955).
60. N.V.Kuznetsov, Candidate's Thesis [Ph.D.Equivalent], Institute of Organic Chemistry of the Academy of Sciences of the USSR, Moscow, 1955.
61. Yu.A.Titov, Candidate's Thesis [Ph.D.Equivalent], Institute of Organic Chemistry of the Academy of Sciences of the USSR, Moscow, 1959.
62. K.Alder and W.Vogt, Annalen., 564, 109 (1949).
63. E.Lehmann and W.Paasche, Ber., 68, 1068 (1935).
64. H.J.Pistor and H.Pleininger, Annalen., 562, 239 (1944).
65. S.Murahashi, B.Ruitani, and Y.Shuto, J.Chem.Soc.Japan, Pure Chem.Sec., 78, 324 (1957).
66. R.Pummerer, F.Aldebert, and H.Sperber, Annalen., 583, 191 (1953).
67. Yu.A.Arbuzov and B.L.Dyatkin, Dokl.Akad.Nauk SSSR, 111, 1249 (1956).
68. H.R.Snyder, H.V.Anderson, and D.P.Hallada, J.Amer. Chem.Soc., 73, 3258 (1951).
69. J.S.Meek, R.T.Merrows, and S.J.Cristol, J.Amer.Chem. Soc., 74, 2667 (1952).
70. L.E.Miller and C.J.Strickler, J.Amer.Chem.Soc., 76, 698 (1954).
71. A.A.Petrov and A.F.Sapozhnikov, Zhur.Obshch.Khim., 18, 424 (1948).
72. J.Meinwald and H.G.Hwang, J.Amer.Chem.Soc., 79, 2910 (1957).
73. I.N.Nazarov, Yu.A.Titov, and A.I.Kuznetsova, Izv.Akad. Nauk SSSR, Otd.Khim.Nauk, 1412 (1959).
74. A.J.Lauck, Diss.Abs., 17, 240 (1957).
75. I.N.Nazarov, Yu.A.Titov, and A.I.Kuznetsova, Izv.Akad. Nauk SSSR, Otd.Khim.Nauk, 1595 (1959).
76. L.E.Miller and D.J.Mann, J.Amer.Chem.Soc., 79, 2910 (1957).
77. Mme.Mousseron-Canet, Bull.Soc.chim.France., 148 (1958).
78. Mme.Mousseron-Canet and Mme.Mousseron, Bull.Soc.chim. France., 391 (1956).
79. Mme.Mousseron-Canet, Bull.Soc.chim.France., 749 (1956).
80. Mme.Mousseron-Canet and M.Granier, Bull.Soc.chim. France., 920 (1958).
81. K.Alder and J.Haydn, Annalen., 570, 201 (1950).
82. J.S.Meek, R.T.Merrow, D.E.Ramey, and S.J.Cristol, J.Amer.Chem.Soc., 73, 5563 (1951).
83. E.Buchta and G.Satzinger, Chem.Ber., 92, 449 (1959).
84. I.N.Nazarov and S.I.Zav'yalov, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk, 1452 (1952).
85. J.S.Meek and W.B.Trapp, J.Amer.Chem.Soc., 74, 2686 (1952).
86. J.Gillois-Doucet, Ann.Chim. (France), 10, 497 (1955).
87. I.N.Nazarov and M.V.Kuvarzina, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk, 599 (1948).
88. A.A.Petrov and N.P.Sopov, Zhur.Obshch.Khim., 17, 2228 (1947).
89. M.F.Shostakovskii, E.N.Prilezhaeva, V.A.Azovskaya, and G.V.Dmitrieva, Zhur.Obshch.Khim., 30, 1123 (1960).
90. A.A.Petrov and N.I.Sopov, Zhur.Obshch.Khim., 17, 1295 (1947).
91. A.A.Petrov and N.P.Sopov, Zhur.Obshch.Khim., 26, 2452 (1956).
92. R.Gaertner, J.Amer.Chem.Soc., 76, 6150 (1954).
93. A.A.Petrov and A.V.Tumanova, Zhur.Obshch.Khim., 26, 2744 (1956).
94. Yu.A.Titov and A.I.Kuznetsova, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk, 1823 (1960).
95. I.N.Nazarov and S.I.Zav'yalov, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk, 703 (1952).
96. H.L.Holmes and K.M.Mann, J.Amer.Chem.Soc., 69, 2000 (1947).
97. A.A.Petrov and M.S.Vladimirova, Zhur.Obshch.Khim., 17, 1543 (1947).
98. I.N.Nazarov and V.F.Kucherov, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk, 1462 (1956).
99. H.Fiesselmann, Ber., 75, 881 (1942).
100. A.A.Petrov, Zhur.Obshch.Khim., 11, 661 (1941).
101. A.A.Petrov, Zhur.Obshch.Khim., 17, 538 (1947).
102. E.A.Braude, E.R.H.Jones, F.Sondheimer, and J.B.Toogood, J.Chem.Soc., 607 (1949).
103. I.N.Nazarov, I.V.Torgov, I.I.Zaretskaya, G.P.Verkholetova, S.N.Ananchenko, and V.M.Andreev, Izv.Akad.Nauk SSSR, Otd.Khim.Nauk, 78 (1953).
104. I.N.Nazarov, V.F.Kucherov, and L.N.Terekhova, Izv. Akad.Nauk SSSR, Otd.Khim.Nauk, 443 (1952).
105. M.Murakami and S.Senoh, Report Sci.Res.Inst. (Japan), 29, 533 (1953); Chem.Abs., 49, 10 249 (1955).
106. M.M.Shemyakin, M.N.Kolosov, M.G.Karapetyan, and E.S.Chaman, Dokl.Akad.Nauk SSSR, 112, 669 (1957).
107. R.L.Clarke and W.S.Johnson, J.Amer.Chem.Soc., 81, 5706 (1959).
108. M.Tanaka, J.Chem.Soc.Japan, Ind.Chem.Sect., 60, 1509 (1957).
109. Yu.A.Titov and A.I.Kuznetsova, Izv.Akad.Nauk SSSR, Otd. Khim.Nauk, 1297 (1960).
110. A.Wassermann, Trans.Faraday Soc., 34, 128 (1938).
111. L.J.Andrews and R.M.Keefer, J.Amer.Chem.Soc., 77, 6284 (1955).
112. D.Rowley and H.Steiner, Discuss.Faraday Soc., 198 (1951).
113. J.B.Harkness, G.B.Kistiakowsky, and W.H.Mears, J.Chem.Phys., 5, 682 (1937).
114. K.Alder and W.Stein, Angew.Chem., 50, 510 (1937).
115. A.Wassermann, J.Chem.Soc., 623 (1942).
116. A.Wassermann, J.Chem.Soc., 612 (1942).
117. W.Rubin and A.Wassermann, J.Chem.Soc., 2205 (1950).
118. R.B.Woodward, J.Amer.Chem.Soc., 64, 3058 (1942).
119. R.B.Woodward and H.Baer, J.Amer.Chem.Soc., 66, 546 (1944).
120. M.C.Kloetzel, "Organic Reactions" (Translated into Russian), Vol.4, Inostr.Lit., Moscow, 1951, p.7.
121. I.N.Nazarov and M.V.Mavrov, Dokl.Akad.Nauk SSSR, 120, 86 (1958).
122. I.N.Nazarov and M.V.Mavrov, Zhur.Obshch.Khim., 28, 3061 (1958).
123. K.Alder and M.Schumacher, Fortschr.Chem.org.Naturstoffe., 16, 1 (1953).
124. M.Mousseron-Canet and J.Boch, Bull.Soc.chim.France., 988 (1957).
125. M.Mousseron-Canet and M.Mousseron, Bull.Soc.chim. France., 601 (1959).
126. M.Mousseron, M.Mousseron-Canet, and J.Boch, Compt. rend., 247, 2073 (1958).
127. M.Mousseron-Canet, Bull.Soc.chim.France., 626 (1957).
128. K.Alder, K.H.Decker, and R.Lienau, Annalen., 570, 224 (1950).
129. I.N.Nazarov, A.I.Kuznetsova, N.V.Kuznetsov, and Yu.A. Titov, Izv.Akad.Nauk SSSR, Otd.Khim.Nauk, 663 (1959).
130. K.Alder, H.H.Mölls, and R.Reeber, Annalen., 611, 7 (1958).
131. K.Alder and M.Schumacher, Annalen., 571, 87 (1951).
132. S.Israelashvili, Y.Gottlieb, M.Imber, and A.Habas,

J. Org. Chem., 16, 1519 (1951).
133. K. Alder and M. Schumacher, Annalen., 571, 122 (1951).
134. K. Alder and W. Vogt, Annalen., 571, 137 (1951).
135. K. Alder, M. Schumacher, and O. Wolff, Annalen., 570, 230 (1950).
136. T. Wagner-Jauregg and E. Helmert, Ber., 71, 2535 (1938).
137. M. W. Rigg and R. Bosenthal, J. Amer. Chem. Soc., 71, 2865 (1949).
138. C. F. H. Allen, A. C. Bell, and J. Van Allan, J. Amer. Chem. Soc., 62, 656 (1940).
139. N. C. Deno and J. D. Johnson, J. Amer. Chem. Soc., 74, 3233 (1952).
140. N. C. Deno, J. Amer. Chem. Soc., 72, 4057 (1950).
141. N. C. Deno and H. Shafetz, J. Org. Chem., 25, 449 (1960).
142. K. Alder, K. Heimbach, and K. Neufang, Annalen., 586, 138 (1954).
143. E. D. Bergmann and R. Barshai, J. Amer. Chem. Soc., 81, 5641 (1959).
144. K. Alder, J. Haydn, K. Heimbach, and K. Neufang, Annalen., 586, 110 (1954).
145. I. N. Nazarov, V. F. Kucherov, and G. M. Segal', Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 559 (1956).
146. I. N. Nazarov and T. D. Nagibina, Zhur. Obshch. Khim., 23, 577 (1953).
147. E. D. Bergmann and A. Becker, J. Amer. Chem. Soc., 81, 221 (1959).
148. F. R. Mayo, "Mezhdunarodnyi Simpozium po Makromolekulyarnoi Khimii, Moskva" (International Symposium on Macromolecular Chemistry, Moscow), 1960, Section II, p. 11.
149. I. N. Nazarov and I. V. Torgov, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 901 (1953).
150. I. N. Nazarov, I. I. Zaretskaya, G. P. Verkholetova, and I. V. Torgov, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 920 (1953).
151. I. N. Nazarov, G. P. Verkholetova, I. V. Torgov, I. I. Zaretskaya, and S. N. Ananchenko, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 929 (1953).
152. I. N. Nazarov, L. I. Shmonina, and I. V. Torgov, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 1074 (1953).
153. I. N. Nazarov, V. F. Kucherov, and G. P. Kugatova, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 487 (1955).
154. W. Davies and B. C. Ennis, J. Chem. Soc., 915 (1959).
155. I. N. Nazarov, S. N. Ananchenko, and I. V. Torgov, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 95 (1959).
156. I. N. Nazarov, V. F. Kucherov, and V. M. Andreev, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 78 (1955).
157. I. N. Nazarov, V. F. Kucherov, and V. M. Andreev, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 89 (1955).
158. E. A. Leporskaya and A. A. Petrov, Zhur. Obshch. Khim., 28, 1432 (1958).
159. R. Y. Baxter, W. L. Norris, and D. S. Morris, J. Chem. Soc., 95 (1949).
160. I. N. Nazarov and I. L. Kotlyarevskii, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 1101 (1953).
161. G. Singh, J. Amer. Chem. Soc., 78, 6109 (1956).
162. W. E. Bachmann and J. M. Chemerda, J. Amer. Chem. Soc., 70, 1468 (1948).
163. J. Heer and K. Meischer, Helv. Chim. Acta., 32, 1572 (1949).
164. I. V. Torgov and I. N. Nazarov, Zhur. Obshch. Khim., 29, 793 (1959).
165. J. Heer and K. Miescher, Helv. Chim. Acta., 31, 219 (1948).
166. E. E. Beyler and L. H. Sarett, J. Amer. Chem. Soc., 74, 1397 (1952).
167. L. H. Sarett, R. M. Lukes, G. I. Poos, J. M. Robinson, R. E. Beyler, J. M. Vandergrift, and G. E. Arth, J. Amer. Chem. Soc., 74, 1393 (1952).
168. I. N. Nazarov and M. V. Mavrov, Zhur. Obsch. Khim., 29, 1158 (1959).
169. V. R. Skvarchenko, Ling Wên-Lien, and R. Ya. Levina, Zhur. Obshch. Khim., 30, 2141 (1960).
170. I. N. Nazarov, V. F. Kucherov, and G. M. Segal', Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 1215 (1956).
171. F. Winternitz and C. Balmossière, Tetrahedron., 2, 100 (1958).
172. M. Mousseron, F. Winternitz, and C. Balmossière, Compt. rend., 243, 1328 (1956).
173. F. Winternitz and G. Balmossière, Bull. Soc. chim. France., 625 (1957).
174. M. F. Ansell and G. T. Brooks, J. Chem. Soc., 4518 (1956).
175. F. Winternitz and C. Balmossière, Bull. Soc. chim. France., 767 (1955).
176. I. N. Nazarov, V. F. Kucherov, V. M. Andreev, and G. M. Segal', Dokl. Akad. Nauk SSSR, 104, 729 (1955).
177. H. W. Voigtländer, Die Pharmazie, 15, 268 (1960).
178. J. Colonge, J. Dreux, and J. P. Regeaud, Bull. Soc. chim. France., 1244 (1959).
179. A. R. Vil'chinskaya and B. A. Arbuzov, Zhur. Obshch. Khim., 29, 2718 (1959).
180. F. Winternitz and C. Balmossiere, Bull. Soc. chim. France., 1550 (1956).
181. F. Winternitz and C. Balmossiere, Bull. Soc. chim. France., 669 (1958).
182. I. N. Nazarov and M. V. Mavrov, Zhur. Obshch. Khim., 29, 1169 (1959).
183. Y. R. Haves and P. Ardizio, Helv. Chim. Acta., 31, 2256 (1948).
184. Y. Fijita and I. Ichikizaki, Bull. Kobayasi Inst. Phys. Res., 8, 138 (1958); Ref. Zhur. Khim., 13333 (1960).
185. A. Arai, Y. Fujita, and I. Ichikizaki, Bull. Kobayasi Inst. Phys. Res., 8, 24 (1958); Ref. Zhur. Khim., 9179 (1960).
186. Y. Fujita, J. Chem. Soc. Japan, Pure Chem. Sec., 80, 450 (1959).
187. A. Arai, Y. Fujita, and I. Ichikizaki, Bull. Kobayasi Inst. Phys. Res., 7, 210 (1957); Ref. Zhur. Khim., 31492 (1959).
188. A. Arai, Bull. Kobayasi Inst. Phys. Res., 8, 207 (1958); Ref. Zhur. Khim., 34934 (1960).
189. O. N. Jitkow and M. T. Bogert, J. Amer. Chem. Soc., 63, 1979 (1941).
190. H. Steiner and H. Schinz, Helv. Chim. Acta., 34, 1176 (1951).
191. J. C. Lunt and F. Sondheimer, J. Chem. Soc., 2957 (1950).
192. J. C. Lunt and F. Sondheimer, J. Chem. Soc., 3361 (1950).
193. J. Alkonyi and D. Szabo, Acta Chim. Acad. Sci. Hung., 12, 289 (1957).
194. R. Ya. Levina, N. N. Godovikova, and F. K. Velichko, Zhur. Obshch. Khim., 25, 2522 (1955).
195. I. N. Nazarov and M. V. Mavrov, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 1068 (1959).
196. H. E. Zimmermann and H. J. Giallombardo, J. Amer. Chem. Soc., 78, 6259 (1956).
197. S. J. Averill and H. L. Trumbull, J. Amer. Chem. Soc., 76, 1159 (1954).
198. M. S. Newman and H. A. Lloyd, J. Org. Chem., 17, 576 (1952).
199. I. N. Nazarov and G. P. Kugatova, Izv. Akad. Nauk SSSR, Otd. Khim. Nauk, 480 (1955).
200. I. N. Nazarov, I. V. Torgov, and M. V. Kuvarzina, Zhur. Obshch. Khim., 22, 220 (1952).
201. I. N. Nazarov and T. D. Nagibina, Zhur. Obshch. Khim., 23, 801 (1953).
202. E. G. Kataev and N. S. Matveeva, Zhur. Obshch. Khim., 23, 405 (1953).
203. E. D. Bergmann, Bull. Res. Council Israel., 5A, 147 (1956); Chem. Abs., 50, 15493 (1956).
204. E. T. McBee, C. W. Roberts, and C. G. Hsu, J. Amer. Chem. Soc., 78, 3393 (1956).
205. R. Ya. Levina, V. R. Skvarchenko, L. A. Chervoneva, L. V. Fedorchuk, and T. T. Vasil'eva, Dokl. Akad. Nauk SSSR, 118, 938 (1958).

206. E.G.Kataev and N.M.Bekmeneva, Uch.Zap.Kazan.Univ., 115, No.3, 13 (1955).
207. H.O.House, W.F.Gannon, R.S.Ro, and D.J.Wluka, J. Amer.Chem.Soc., 82, 1463 (1960).
208. R.Adams and R.B.Carlin, J.Amer.Chem.Soc., 65, 360 (1943).
209. E.C.Taylor and E.J.Strojny, J.Amer.Chem.Soc., 78, 5104 (1956).
210. R.J.Longley and W.S.Emesson, J.Amer.Chem.Soc., 72, 3079 (1950).
211. N.K.Kochetkov and G.V.Aleksandrova, Dokl.Akad.Nauk SSSR, 85, 1033 (1952).
212. W.C.Wildman, R.B.Wildman, W.T.Norton, and J.B. Fine, J.Amer.Chem.Soc., 75, 1912 (1953).
213. H.Burkett and W.Wright, J.Org.Chem., 25, 276 (1960).
214. W.Dilthey and G.Hurtig, Ber., 67, 2004 (1934).
215. C.F.Allen and J.Van Allan, J.Org.Chem., 10, 333 (1945).
216. K.Alder and E.Windemuth, Annalen., 543, 41 (1939).
217. D.Y.Curtin and R.R.Fraser, J.Amer.Chem.Soc., 81, 662 (1959).
218. J.S.Meek, J.R.Dann, and B.T.Poon, J.Amer.Chem.Soc., 78, 5413 (1956).
219. J.S.Meek, B.T.Poon, and S.J.Cristol, J.Amer.Chem. Soc., 74, 761 (1952).
220. J.S.Meek and J.R.Dann, J.Org.Chem., 21, 968 (1956).
221. J.S.Meek, D.R.Wilgus, and J.R.Dann, J.Amer.Chem. Soc., 82, 2566 (1960).
222. H.W.B.Reed, J.Chem.Soc., 685 (1951).
223. E.Vogel, Angew.Chem., 68, 413 (1956).
224. R.E.Foster and R.S.Schreiber, J.Amer.Chem.Soc., 70, 2303 (1948).
225. K.Ziegler and H.Wilms, Annalen., 567, 1 (1950).
226. K.Alder, J.Haydn, and W.Vogt, Chem.Ber., 86, 1302 (1953).
227. J.L.Charlish and W.H.Davies, J.Chem.Soc., 1385 (1950).
228. H.R.Snyder and G.I.Poos, J.Amer.Chem.Soc., 71, 1395 (1949).
229. K.Alder and W.Vogt, Annalen., 570, 190 (1950).
230. T.F.Bradley and R.W.Tess, Ind.Eng.Chem., 41, 310 (1949).
231. I.N.Nazarov, N.V.Kuznetsov, and A.I.Kuznetsova, Zhur. Obshch.Khim., 25, 320 (1955).
232. I.N.Nazarov, G.P.Verkholetova, and L.D.Bergel'son, Izv. Akad.Nauk SSSR, Otd.Khim.Nauk, 511 (1948).
233. A.T.Blomquist and J.C.Westfahl, J.Amer.Chem.Soc., 75, 2304 (1953).
234. N.L.Klebanskii and M.M.Denisova, Zhur.Obshch.Khim., 17, 703 (1947).
235. I.N.Nazarov and A.I.Kuznetsova, Zhur.Obshch.Khim., 30, 139 (1960).
236. C.S.Marvel and N.O.Brace, J.Amer.Chem.Soc., 71, 37 (1949).
237. C.C.Price, G.A.Cypner, and L.V.Krishnamurti, J.Amer. Chem.Soc., 74, 2987 (1952).
238. E.A.Braude and E.A.Evans, J.Chem.Soc., 3238 (1956).
239. S.V.Lebedev, Zhur.Russ.Fiz.-Khim.Obshch., 45, 1249 (1913).
240. O.Aschan, Annalen., 461, 1 (1928).
241. T.Wagner-Jauregg and A.Lennartz, Chem.Ber., 80, 553 (1947).
242. G.Salomon, B.Boonstra, S.van der Meer, and A.Ultee, Rubber Chem.Technol., 22, 956 (1949).
243. A.I.Zakharova and V.A.Bezel'-Sycheva, Zhur.Obshch. Khim., 11, 67 (1941).
244. I.N.Nazarov, A.I.Kuznetsova, and N.V.Kuznetsov, Zhur. Obshch.Khim., 25, 307 (1955).
245. Y.L.Binder, K.S.Eberly, and G.E.P.Smith, J.Polymer Sci., 38, 229 (1959).
246. C.Walling and J.Peisach, J.Amer.Chem.Soc., 80, 5819 (1958).
247. I.N.Nazarov and A.I.Kuznetsova, Zhur.Obshch.Khim., 30, 134 (1960).
248. A.A.Petrov and R.A.Shlyakhter, Dokl.Akad.Nauk SSSR, 75, 703 (1950).
249. A.A.Petrov and R.A.Shlyakhter, Trudy VNIISK, 3, 51 (1951).
250. H.R.Snyder and G.I.Poos, J.Amer.Chem.Soc., 72, 4096 (1950).
251. H.R.Snyder and G.I.Poos, J.Amer.Chem.Soc., 71, 1057 (1949).
252. W.E.Hahn, Wiadom.Chem., 9, 616 (1955).
253. G.Dumas and R.Rumpf, Compt.rend., 242, 2574 (1956).
254. J.M.Bremner, D.G.Jones, and S.Beaumont, J.Chem.Soc., 1018 (1946).
255. C.W.Smith, D.G.Norton, and S.A.Ballard, J.Amer.Chem. Soc., 73, 5267 (1951).
256. C.W.Smith, D.G.Norton, and S.A.Ballard, J.Amer.Chem. Soc., 73, 5270 (1951).
257. C.W.Smith, D.G.Norton, and S.A.Ballard, J.Amer.Chem. Soc., 73, 5274 (1951).
258. K.Alder, H.Offermann, and E.Rüden, Ber., 74, 905 (1941).
259. K.Alder and E.Rüden, Ber., 74, 920 (1941).
260. W.J.Dale and A.J.Sisti, J.Org.Chem., 22, 449 (1957).
261. T.L.Gresham and T.R.Steedman, J.Amer.Chem.Soc., 71, 737 (1949).
262. G.J.Janz and A.G.Keenan, Canad.J.Res., 25B, 272 (1947).
263. G.J.Janz and S.C.Wait, J.Amer.Chem.Soc., 76, 6377 (1954).
264. G.J.Janz and W.J.McCulloch, J.Amer.Chem.Soc., 77, 3143 (1955).
265. R.Madronero, E.F.Alvarez, and M.Lora-Tamayo, Anales real Soc.españ.Fís.Quím., 51B, 276 (1955).
266. R.Madronero, E.F.Alvarez, and M.Lora-Tamayo, Anales real Soc.españ.Fís.Quím., 51B, 465 (1955).
267. O.Wichterle and M.Kolinsky, Chem.Listy., 47, 1787 (1953).
268. O.Wichterle and V.Gregor, Chem.Listy., 51, 605 (1957).
269. Yu.A.Arbuzov and T.A.Pisha, Dokl.Akad.Nauk SSSR, 116, 71 (1957).
270. Ya.K.Syrkin and I.I.Moiseev, Uspekhi Khim., 27, 1321 (1958).
271. Ya.K.Syrkin, Izv.Akad.Nauk SSSR, Otd.Khim.Nauk, 238 (1959).
272. R.Robinson, "Outline of the Electrochemical Theory of the Course of Organic Reactions", The Institute of Chemistry of Great Britain and Ireland, 1932, p.29.
273. G.E.Branch and M.Calvin, "The Theory of Organic Chemistry", Prentice-Hall, New York, 1944, p.487.
274. A.E.Remick, "Electronic Interpretations of Organic Chemistry", New York, 1949, p.447.
275. C.K.Ingold, "Structure and Mechanism in Organic Chemistry" (Translated into Russian), Inostr.Lit., Moscow, 1959, p.567.
276. S.Irie, J.Japan Chem., 7, 16 (1953).
277. C.C.Price, "Mechanisms of Reactions of Carbon-Carbon Double Bonds", Interscience Publ., New York, 1946, p.49.
278. R.P.Alvarez-Ossorio and M.Sanz Burata, Afinidad, 31, 523 (1953).
279. R.Bergmann, H.E.Eschinazi, and M.Neeman, J.Org. Chem., 8, 179 (1943).
280. F.Bergmann and H.E.Eschinazi, J.Amer.Chem.Soc., 65, 1405 (1943).
281. J.Mathieu and J.Valls, Bull.Soc.chim.France., 1509 (1957).
282. B.A.Arbuzov and A.I.Konovalov, Izv.Akad.Nauk SSSR, Otd.Khim.Nauk, 2131 (1959).
283. B.A.Arbuzov and A.I.Konovalov, Izv.Akad.Nauk SSSR, Otd.Khim.Nauk, 68 (1960).
284. G.B.Kistiakowsky and J.R.Lacher, J.Amer.Chem.Soc., 58, 123 (1936).
285. G.B.Kistiakowsky and W.W.Ransom, J.Chem.Phys., 7, 725 (1939).

286. N.N.Semenov, "O Nekotorykh Problemakh Khimicheskoi Kinetiki i Reaktsionnoi Sposobnosti" (Some Problems of Chemical Kinetics and Reactivity), Izv.Akad.Nauk SSSR, Moscow, 1958, p.404.
287. H.Henecka, Naturforsch., 4, 15 (1949).
288. J.I.C.Cadogan and D.H.Hey, Quart.Rev., 8, 308 (1954).
289. F.R.Mayo and C.Walling, Chem.Rev., 27, 351 (1940).
290. I.V.Torgov, Doctoral Thesis (D.Sc.Equivalent), Institute of Organic Chemistry of the Academy of Sciences of the USSR, Moscow, 1953.
291. C.A.Coulson, Research., 4, 307 (1951).
292. D.R.Augood and G.T.Willams, Chem.Rev., 57, 123 (1957).
293. F.H.Burkitt, C.A.Coulson, and H.C.Longuet-Higgins, Trans.Faraday Soc., 47, 553 (1951).

Zelinskii Institute of Organic Chemistry,
Academy of Sciences of the USSR

CYCLISATION REACTIONS BASED ON ACRYLONITRILE

P. F. Butskus

CONTENTS

1. Acrylonitrile in diene synthesis 283
2. Acrylonitrile in other reactions involving ring formation 284
3. Cyclisation of cyanoethylated compounds preserving the 2-cyanoethyl group 285
4. Cyclisation of cyanoethylated compounds involving the 2-cyanoethyl group 286
(*a*) *O*-Cyanoethylated compounds 286
(*b*) *S*-Cyanoethylated compounds 286
(*c*) *N*-Cyanoethylated compounds 286
(*d*) *C*-Cyanoethylated compounds 287
(*e*) *As*- and *P*-Cyanoethylated compounds 289

Both acrylonitrile itself and the cyanoethylated compounds synthesised with its help[1-4] are widely employed for obtaining both simple and complex ring systems. Almost all the investigations in this field have been published during the past fifteen years. The starting materials for these reactions are in most cases readily available.

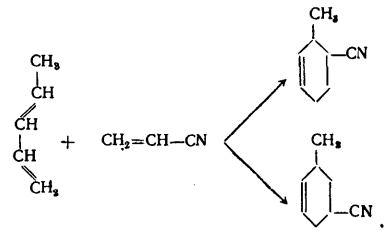
The use of acrylonitrile and cyanoethylated compounds in reactions involving ring formation is of interest from the point of view of both theory and preparative work, as it enables various cyclic systems to be synthesised, including those containing the cyanoethyl group, that either cannot be obtained by other methods or else can be so obtained only in poor yields.

1. ACRYLONITRILE IN DIENE SYNTHESIS

Acrylonitrile acts as a dienophile in reactions involving the Diels-Alder diene synthesis.

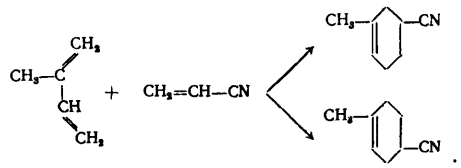
Condensation of butadiene with acrylonitrile results in the formation of cyclohex-3-enyl cyanide[1,3,5-12], although under some conditions it is assumed that 2-vinyldihydropyridine is formed as well[12].

Two structural isomers can theoretically be formed in condensations of 1-substituted dienes with acrylonitrile. It was considered for a long time that such reactions yield exclusively the *ortho*-isomer. In 1947, however, Frank *et al.*[13] demonstrated the presence of a small quantity of the *meta*-isomer in the mixture of adducts obtained by the condensation of penta-1,3-diene with acrylonitrile. The structural orientation of diene synthesis was subsequently studied in detail by Nazarov and his coworkers[14,15], who showed that the condensation of 1-substituted dienes with acrylonitrile yields a mixture of the two possible adducts containing 85–95% of the *ortho*-isomer and 5–15% of the *meta*-isomer. For example, in the case of penta-1,3-diene the reaction proceeds as follows:

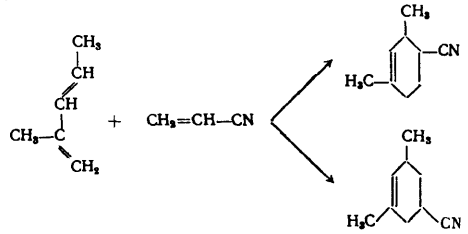


Other workers have also investigated[5,16-21] the interaction of penta-1,3-diene with acrylonitrile.

In the condensation of 2-substituted dienes with acrylonitrile, the orienting effect of the substituent in the diene molecule results in preferential formation of *para*-adducts[14,15]. In the case of isoprene[16,17,22-24] the process takes place according to the scheme



The interaction of 1,2-dimethylbutadiene (3-methylpenta-1,3-diene) with acrylonitile gives mainly 2,3-dimethylcyclohex-3-enyl cyanide and a small quantity of 4,5-dimethylcyclohex-3-enyl cyanide[14]. Reaction of 1,3-dimethylbutadiene (2-methylpenta-1,3-diene) with acrylonitrile produces mainly 2,4-dimethylcyclohex-3-enyl cyanide and also a small amount of the "symmetrical" isomer[15]:



Heating diethyl *trans–trans*-muconate with acrylonitrile in the presence of quinol at 160°–170° for 30 h gives a 64%