Translated from *Uspekhi Khimii*, **56**, 95-127 (1987) U.D.C. 547.913.5

# Pseudoazulenes as π-Isoelectronic Analogues of Azulene

Yu.N.Porshnev, V.A.Churkina, and M.I.Cherkashin

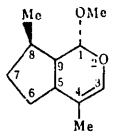
The principal methods of synthesis and the chemical and physicochemical properties of pseudoazulene are described. Attention is concentrated on the latest studies which have not been taken into account in the published reviews. Certain aspects of the uses of pseudoazulene compounds are examined.
The bibliography includes 185 references.

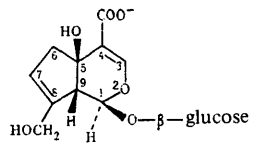
CONTENTS

I. Introduction 52
II. Methods of synthesis of pseudoazulenes 54
III. Chemical properties 57
IV. Quantum-chemical calculations 62
V. Physicochemical properties 63
VI. Biological activity and practical applications of pseudoazulenes 65

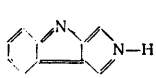
## I. INTRODUCTION

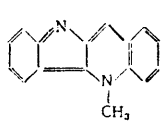
Only individual terpenoid representatives of hydrogenated pseudoazulenes of the cyclopentapyran series, such as 1-methoxymyodesert-3-ene (I) which forms part of the structure of *Myoporum deserti* (Myoporaceae) as the iridoid constituent and has been found in plants growing in the moist regions of Australia, have been discovered in nature.[1] The iridoid—the glycoside (II)—present in *Lanthana camara* (Verbenaceae) and detected in 150 plant species in Africa and tropical America, has been identified:


(I)

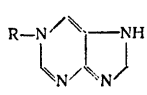

(II)

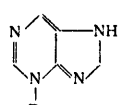
Individual pseudoazulene systems are components in the structures of alkaloids. Thus the alkaloids sempervirine and alstonine contain the 2*H*-pyrido[3,4-*b*]indole (III) system,[3-7] while the alkaloid cryptolepine has the structure (IV).[8] The hydrogenated indolizine system (V) is present in the molecules of strychnine, securinine, and the Veratrum alkaloids germine, cevine, and protoverine. The 1- and 3-alkylpurines (VI) and (VII) are used as model substances which participate in glycosylation reactions and whose reactivity is equal to that of antibiotics and nucleic acids.[9,10]


(III)


(IV)

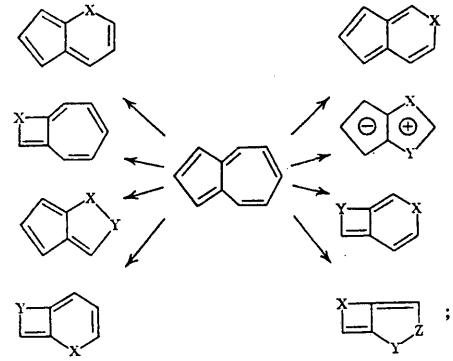

(V)


(VI)


(VII)

The advances in quantum chemistry regarding the creation of the theory of aromaticity have promoted an intense development during the last three decades of the chemistry of heterocarbonium aromatic systems, among which analogues of the non-benzenoid aromatic azulene system, namely pseudoazulenes, are of special interest. Formally, they can be obtained by replacing a two-electron carbon–carbon double bond in the aromatic system by the unshared electron pair of the heteroatom, whereupon the aromatic character of the system is usually retained.[11-13] This principle of structural analogy, which has been known for a long time in the benzene–thiophen–furan–pyrrole series, was first applied in 1957 by Boyd[14] and Mayer[15] and later also by other workers[16,17] to a large group of heterocyclic compounds—pseudoazulenes, which are π-isoelectronic analogues of azulene. The chemistry of these systems has only just begun to develop despite the fact that the fundamental studies by Robinson and co-workers[11-13] were published in the first quarter of this century.

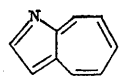
According to the above principle, numerous representatives of pseudoazulene systems in which one, two, or three double bonds have been replaced by heteroatoms can be formally obtained from azulene:

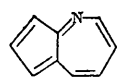


X, Y, Z = –O–, –S–, –NR–, –Se–, –Te–.

For the azazulenes (VIII) and (IX), polyazazulenes, and heteroniaazulenes, the analogous "reactions" are also possible.[18,19]

The number of possible systems increases greatly when different heteroatoms are used simultaneously. Dinuclear condensed heterocyclic systems with a nitrogen atom common to both rings, namely quinolizines, are also regarded as the pseudoazulenes (V) and (X).


(VIII)


(IX)

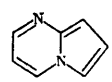
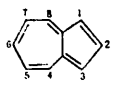
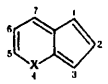
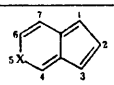
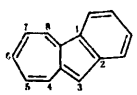
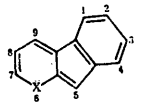
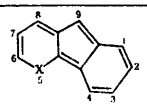
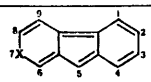
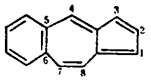
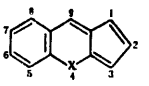
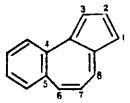
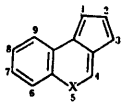
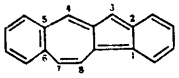
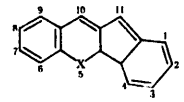
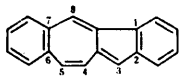
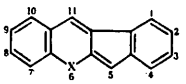
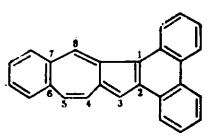
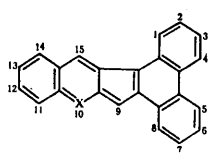

(X)

**Table 1. Pseudoazulenes with one heteroatom in the six-membered ring.**

| Azulene | Pseudoazulene | Code | X | Name | | Refs. |
|---|---|---|---|---|---|---|
| | | | | in IUPAC nomenclature | trivial | |
| | | | 10 π-Electron systems | | | |
|  azulene |  | (XI) | NR | 1H-pyrindine | azalene | [12, 13, 51, 60, 73] |
| | | (XII) | O | cyclopenta[b]pyran | oxalene | [14, 51, 53, 102] |
| | | (XIII) | S | cyclopenta[b]thiapyran | thialene | [15, 18, 34, 35, 106] |
| |  | (XIV) | NR | 2H-pyrindine | isoazalene | [36, 37, 62, 72, 110] |
| | | (XV) | O | cyclopenta[c]pyran | iso-oxalene | [62] |
| | | (XVI) | S | cyclopenta[c]thiapyran | isothialene | [34—37, 61—64] |
| | | | 14 π-Electron systems | | | |
|  1,2-Benzoazulene |  | (XVII) | NR | 6H-indeno[2,1-*b*]pyridine | 1,2-benzoazalene | [101] |
| | | (XVIII) | O | indeno[2,1-*b*]pyran | 1,2-benzoxalene | [104] |
| | | (XIX) | S | indeno[2,1-*b*]thiapyran | 1,2-benzothialene | [34] |
| |  | (XX) | NR | 5H-indeno[1,2-*b*]pyridine | 2,3-benzoazalene | [59] |
| | | (XXI) | S | indeno[1,2-*b*]thiapyran | 2,3-benzothialene | [55] |
| |  | (XXII) | NR | 7H-indeno[2,1-*c*]pyridine | 1,2-benzoisoazalene | [66—68, 116] |
|  5,6-Benzoazulene |  | (XXIII) | NR | 4H-cyclopenta[*b*]quinoline | 5,6-benzoazalene | [16, 19, 43—46] |
| | | (XXIV) | O | cyclopenta[*b*]chromene | 5,6-benzoxalene | [14, 16, 25, 57] |
| | | (XXV) | S | cyclopenta[*b*]thiachromene | 5,6-benzothialene | [25, 28, 38] |
|  4,5-Benzoazulene |  | (XXVI) | NR | 5H-cyclopenta[*c*]quinoline | 7-benzoisoazalene | [29] |
| | | | 18 π-Electron systems | | | |
|  1,2; 5,6-Dibenzoazulene* |  | (XXVII) | NR | 5H-indeno[1,2-*b*]quinoline | 2,3; 5,6-dibenzoazalene | [12, 13, 27] |
|  1,2; 6,7-Dibenzoazulene |  | (XXVIII) | NR | 6H-indeno[2,1-*b*]quinoline | 1,2; 5,6-dibenzoazalene | [28, 52, 74, 103] |
| | | (XXIX) | O | indeno[2,1-*b*]chromene | 1,2; 5,6-dibenzoxalene | [14, 26, 28, 57, 74, 77, 80, 103—105] |
| | | (XXX) | S | indeno[2,1-*b*]thiachromene | 1,2; 5,6-dibenzothialene | [34, 49, 111] |
| | | | Systems containing more than 18 π-electrons | | | |
|  Phenanthro[9,10-*a*]-6,7-benzoazulene* |  | (XXXI) | NR | 10H-dibenzo[4,5; 6,7]-indeno-[2,1-*b*]quinoline | phenanthro[9,10-*a*]-5,6-benzoazalene | [24] |

*Azulene systems having this structure are unknown.

They constitute a large independent group of pseudoazulenes, whose chemistry has been described in a monograph.[20] A review has been devoted to the chemistry of the indolizines (V).[21] Almost all the pseudoazulene systems known at the present time are represented in the review of Timpe and El'cov.[22]

The number of existing nitrogen-containing pseudoazulenes is much greater than that of the sulphur- and oxygen-containing compounds; only one pseudoazulene system containing selenium as the heteroatom is known.[23] Systems containing tellurium as well as systems with a four-membered ring are so far unknown, which can be explained by the instability of

these products in the former case or the considerable angular ring strain in the latter. The influence of the heteroatom on the electronic structure, the electronic spectra, the stability, and the reactivity has been most fully investigated for pseudoazulene systems in which the unshared electron pair of the heteroatom replaces one double bond in the seven-membered ring of azulene or benzoazulenes. For this reason, we shall confine ourselves to the consideration of the systems presented in Table 1.

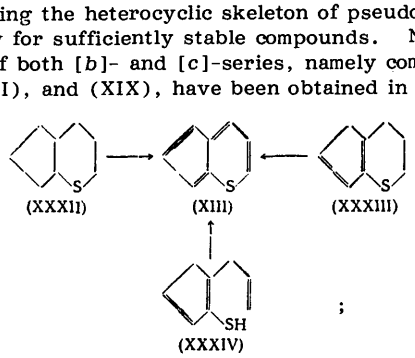
The [*b*]-series pseudoazulenes (XI)–(XIII) and the [*c*]-series pseudoazulenes (XIV) and (XVI) are non-alternant 10π-isoelectronic analogues of azulene. Compounds (XVII) to (XXVI) are isoanalogues of the 14π-electron systems of 1,2-, 5,6-, and 4,5-benzoazulenes. For the 18π-electron systems (XXVII) and (XXX), azulenes with an analogous structure are so far unknown and this is also true of the new pseudoazulene system (XXXI) obtained in 1975.[24] It was initially suggested that pseudoazulenes containing a sulphur atom, an oxygen atom, or an NR group be designated as thialenes,[15] oxalenes,[25] and azalenes[17] respectively. This nomenclature, based on the type of heteroatom, is not always used although it effectively explains the genetic relation with azulene. Specific compounds are usually named in accordance with IUPAC rules, the pyrindines (XI) and (XIV) constituting an exception. The compounds listed in Table 1 are arranged in such a way that the cyclopentane ring is placed on the right-hand side of the main pseudoazulene system, while the heteroatom on the left-hand side is placed in the lower half of the heterocycle. The first carbon atom is located in the upper angle of the cyclopentane component of the main system. The remaining atoms are numbered clockwise, the heteroatom being numbered in accordance with the general sequence. The above nomenclature is most widely used and has already been adopted in a series of well known publications.[14,26–29]

## II. METHODS OF SYNTHESIS OF PSEUDOAZULENES

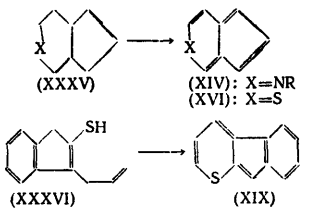
The methods of synthesis of pseudoazulenes differ significantly from those for azulenes, since its molecular skeleton is obtained in different ways, depending on the required pseudoazulene system. The methods of synthesis can be combined, for example, in accordance with the type of the last stage leading to pseudoazulenes. A common stage of this kind in the syntheses of both pseudoazulenes and azulenes is the dehydration of saturated compounds.

### 1. Dehydrogenation of Saturated Precursors of Pseudoazulenes

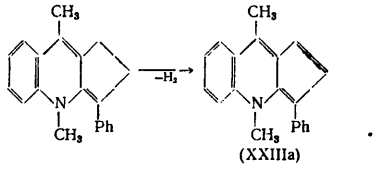
Historically the first and for a long time the only method of synthesis of azulene hydrocarbons was dehydrogenation of bicyclic precursors with the bicyclo[5.3.0]decane structure or the corresponding partly saturated compounds.[30–33] The dehydrogenation of more or less hydrogenated compounds, already having the heterocyclic skeleton of pseudoazulenes, is used only for sufficiently stable compounds. Numerous thialenes, of both [*b*]- and [*c*]-series, namely compounds (XIII), (XVI), and (XIX), have been obtained in this way.




;

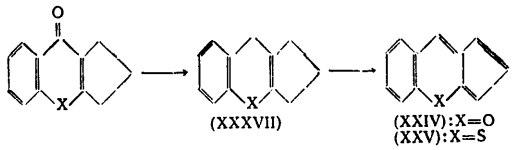



Hydrogenated sulphur-containing heterocycles, for example, compounds (XXXII), (XXXIII), and (XXXV), or the open-chain mercaptans (XXXIV) and (XXXVI),[34] are dehydrogenated in the gas phase over Pd/C at 300–350 °C.[35–38] The overall yield depends on the dehydrogenation stage, which frequently proceeds with a high (~30%) yield; it can also amount to only a few per cent owing to the low activity of the catalyst.[37] However, this method is still the best procedure for the synthesis of not only thialenes but also 2-phenylpyrindine (XIV).[36] Other pseudoazulene systems, for example, substituted 4*H*-cyclopenta[*b*]quinoline (XXIIIa), can also be conveniently obtained in this way,[17] but the dehydrogenation is carried out in boiling xylene for 10 h in an atmosphere of nitrogen with the same catalyst and the yield is 53%.



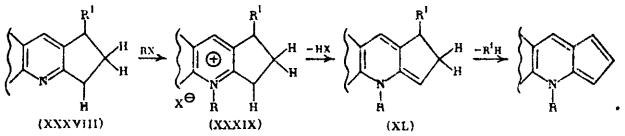

On dehydrogenation over Pd/C and also when the $Cu_2Cl_2$/C catalysts are used at 300 °C or sulphide is used at 300 °C, oxygen-containing precursors [for example, compound (XXXIII, X = O)] give rise to only tarry products.[37]

Azulene precursors are dehydrogenated under very mild conditions by chloranil and for this reason, the latter is widely used in the synthesis of azulenes containing substituents unstable at high temperatures.[39–42] For effective dehydrogenation, it is essential that the precursor should already possess a high degree of unsaturation. Chloranil has been used extremely rarely for the synthesis of pseudoazulenes.[25,35] The synthesis of the unsubstituted pseudoazulenes (XXIV) and (XXV) from chromone and thiachromone respectively using the dehydrogenation of compound (XXXVII, X = O or S) by chloranil has been described,[25] but the author did not indicate the dehydrogenation conditions and the reaction products were not isolated in a pure form:




A number of workers observed the interaction of chloranil with pseudoazulenes, for example, with 4*H*-cyclopenta[*b*]quinoline (XXIII) and 5*H*-cyclopenta[*c*]quinoline (XXVI), the latter being substituted by the chloranil residue in the 1- and 3-positions.[29,43,44]

Dehydro-compounds of the type of (XXXVIII) can be converted into fully aromatic systems by the multistage elimination of hydrogen atoms in the saturated cyclopentane or cyclopentene rings, or by the dehydrohalogenation of quaternary salts, or by some other elimination reaction:

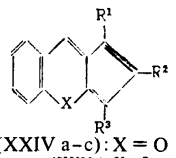


(XXXVIII) (XXXIX) (XL)

The acid-catalysed elimination of water from the hydroxy-derivative (XL, $R^1$ = OH) proceeds especially effectively.[45,46] It is then essential to maintain appropriate conditions exactly, since pseudoazulenes can be decomposed by acid. An instance of photochemical dehydrogenation is known.[24]

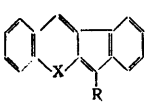
## 2. Condensation of Aromatic Aldehydes and Ketones

The method considered above is a general procedure for the conversion of compounds already containing the pseudoazulene skeleton into pseudoazulenes proper. Since new C–C and C–X bonds can arise in condensation reactions, it is always possible to select suitable initial compounds which give rise to the pseudoazulene system; dehydrogenation is then altogether unnecessary. The form of the initial compounds can be specified by the required structure of the final product. For example, the condensation of salicylaldehyde or *o*-mercaptobenzaldehyde with aryl-substituted $\Delta^2$-cyclopentenones in the presence of piperidinium acetate in benzene yielded the arylsubstituted benzo[*b*]cyclopenta[*e*]pyrans {or cyclopenta[*b*]chromenes} (XXIVa–c)[14,27,47] and the corresponding thiapyrans {or cyclopenta[*b*]thiachromenes} (XXV*a*):[28]



(XXIV a–c): X = O
(XXV*a*): X = S
a: $R^1$=$R^3$=H; $R^2$=Ph [14, 47]
b: $R^1$=$R^2$=Ph; $R^3$=H [27]
c: $R^1$=H; $R^2$=$R^3$=Ph [28]

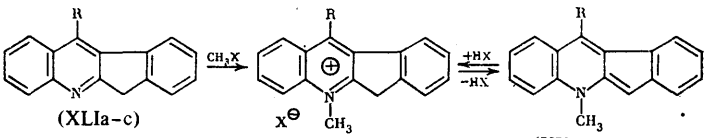
This method is particularly convenient for the synthesis of tetracyclic pseudoazulenes which are sometimes formed in a yield up to 80%. Indeno[2,1-*b*]chromene (XXIXa) and indeno[2,1-*b*] thiachromenes (XXX, R = H) have been obtained by condensing 2-indanone with salicylaldehyde and *o*-mercaptobenzaldehyde respectively.[28,48,49] The condensation of substituted 2-indanones or 2-indanoneimines with salicylaldehyde leads to 5-substituted derivatives of indeno[2,1-*b*]chromene



(XXIX a–e): X=O
(XXX): X=S [28, 49]

a: R = H (Refs.14,48)
b: R = $CH_3$ (Ref.50)
c: R = 2-indanyl (Ref.50)
d: R = $COOC_2H_5$ (Ref.50)
e: R = CN (Ref.28).

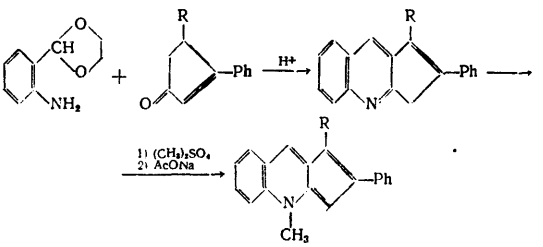
However, nitrogen-containing pseudoazulenes cannot be obtained in this way; the attempts to carry out the condensation in a neutral or alkaline medium (alkali in alcohol or piperidine in benzene) do not yield the final products directly. The reaction of the ethylene acetal of *o*-aminobenzaldehyde with phenyl-$\Delta^2$-cyclopentenones does not afford pseudoazulenes under these conditions and it does not even give rise to Claisen condensation products.[51] The condensation of 2-indanone with *o*-aminobenzaldehyde, *o*-aminoacetophenone, or *o*-aminobenzophenone in an acid medium results in the formation of compounds (XLIa–c), dehydrogenated to the optimum extent, which are converted by quaternisation and subsequent alkaline cleavage of the quaternary salts into nitrogen-containing pseudoazulenes (XXVIIIa–c) in approximately 25% yield:[52]



(XLIa–c)
a: R = H
b: R = $CH_3$
c: R = Ph

(XXVIIIa–c)

Since *o*-aminobenzaldehyde is unstable, it is possible to use its ethylene acetal, whose condensation with 3-phenyl- and 3,4-diphenyl-$\Delta^2$cyclopentenones in alcoholic solution of hydrochloric acid leads to the pseudoazulenes (XXIIIb, c) in good yield (up to 80%):[51,53]

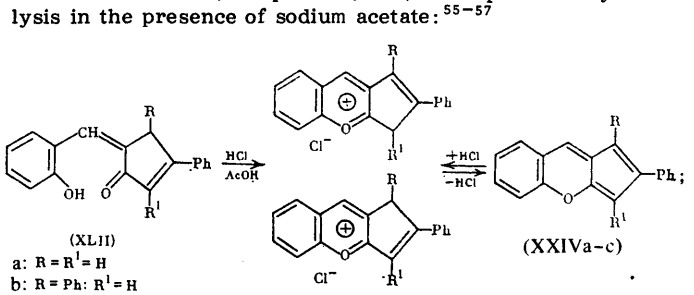


(XXIIIb, c)

## 3. Deprotonation of Pyridinium, Quinolinium, Pyrylium, and Thiapyrylium Salts

The deprotonation of heteronium salts as a method of synthesis of pseudoazulene systems is logically a continuation of the previous subsection and is closely related to it in the synthetic sense, because the majority of the intermediates and salts based on them are obtained in this instance by condensing aldehydes and aromatic (and also α,β-unsaturated) ketones. The deprotonation of heteronium salts actually constitutes the dehydrogenation stage, which completes the synthesis of the pseudoazulene, but, since the number of final systems obtained in this way is fairly large and the reaction itself does not proceed smoothly with all salts, we shall consider this stage in a separate Section.

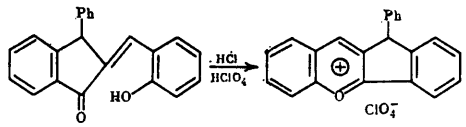
Salicylaldehyde undergoes the Claisen condensation with phenyl-substituted $\Delta^2$-cyclopentenones of 1-indanone in alkaline media with formation of the corresponding hydroxychalcones (XLII) or (XLIII),[54,55] which afford the benzopyrylium salts (XLIVa–c) and (XLV) in a mixture of acetic and hydrochloric acids. However, whereas a solution of the salts (XLIVa–c) gives rise to the pseudoazulenes (XXIVa–c) on dilution with water, compound (XLV) decomposes on hydrolysis in the presence of sodium acetate:[55–57]



(XLII)
a: R = $R^1$ = H
b: R = Ph; $R^1$ = H
c: R = H; $R^1$ = Ph

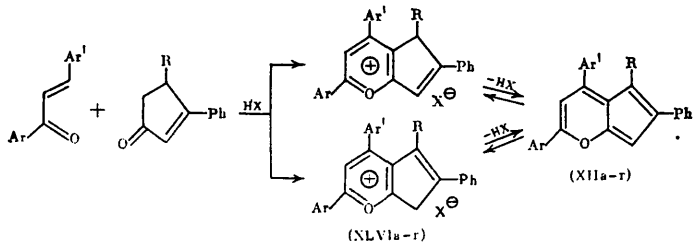
(XLIVa–c)

(XXIVa–c)



(XLIII) (XLV)

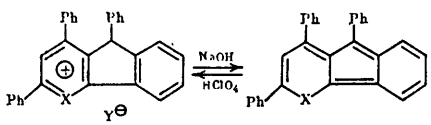
Chalcones and derivatives of phenyl-substituted $\Delta^2$-cyclopentenones condense on treatment with $FeCl_3$ in acetic anhydride into the chloroferrates (XLVIa–d) in 35% yield. On treatment with sodium acetate, both the chloroferrates and perchlorates (XLIVa–d) give rise to cyclopenta[*b*]pyrans (XXIIa–d) in high yields (up to 90%):[47,58,59]



(XLVIa–r) (XIIa–r)

a: R = H, Ar = Ar' = Ph; b: R = Ar = Ar' = Ph; c: R = Ph, Ar = *n*-$CH_3OC_6H_4$, Ar' = Ph; d: R = Ph, Ar = Ph, Ar' = *p*-$CH_3OC_6H_4$; $X^- = FeCl_4^-$, $ClO_4^-$.

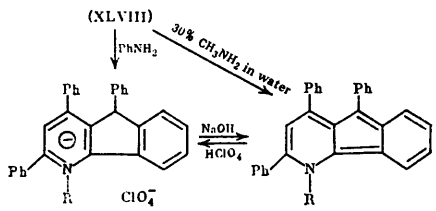
The tetrachloroferrate (XLVI) has been obtained analogously by the reaction of benzylidenacetophenone with 3-phenyl-1-indanone (XLVII) (yield 48%) and was converted into the perchlorate (XLVIII) by treatment with 70% perchloric acid. The condensation of equimolar amounts of acetophenone with 2-benzylidene-3-phenyl-1-indanone gives rise to the chloroferrate (XLVII) in only 20% yield:[55]



(XLVII): X = O, Y = $FeCl_4$ (XXIa): X = S
(XLVIII): X = O, Y = $ClO_4$
(XLIX): X = S, Y = $ClO_4$

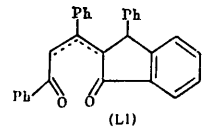
On treatment with a 10% aqueous solution of $Na_2S$ and subsequent addition of 20% perchloric acid, the perchlorate (XLVIII) gives rise to the thiapyrylium salt (XLIX) (yield 93%), which is deprotonated with an aqueous alcoholic solution of alkali and sodium acetate to form 2,4,5-triphenylindeno[1,2-*b*]thiapyran (XXIa). Hot water also hydrolyses the salt (XLIX) but more slowly.

On interaction with aniline, the perchlorate (XLVIII) is converted into the *N*-phenylpyridinium salt (La) in 59% yield. The deprotonation of the salt with aqueous-alcoholic alkali affords 1,2,4,5-tetraphenyl-1*H*-indeno[1,2-*b*]pyridine (XXa). Treatment of the same perchlorate (XLVIII) with 30% aqueous methylamine leads to a 55% yield of 1-methyl-2,4,5-triphenyl-1*H*-indeno[1,2-*b*]pyridine (XXb), which can be converted into the substituted *N*-methylpyridinium perchlorate (Lb):



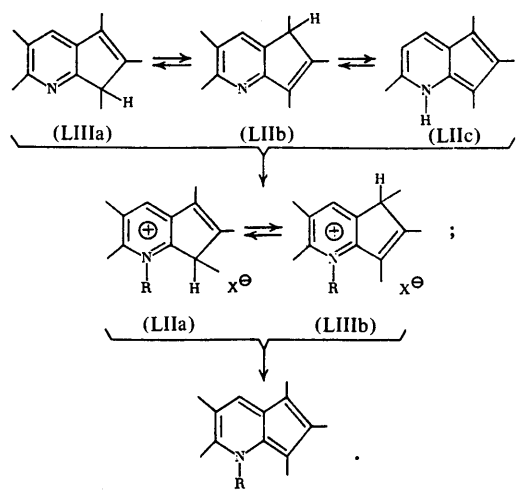
(La): R = Ph (XXa, b)
(Lb): R = $CH_3$

Whereas the heteronium salts of phenyl-substituted derivatives of cyclopenta[*b*]chromene (XLIV), cyclopenta[*b*]pyran (XLVI), indeno[1,2-*b*]thiapyran (XLIX), and indeno[1,2-*b*]-pyridine (L) produce the corresponding pseudoazulenes on hydrolysis with aqueous-alcoholic solutions of alkali or sodium acetate, indeno[1,2-*b*]chromylium perchlorate (XLV) and indeno[1,2-*b*]pyrylium perchlorate (XLVIII) only regenerate the initial compounds under the same conditions, i.e. 3-phenyl-2-salicylidene-1-indanone (XLIII) and 2-(3-oxo-1,3-diphenylpropylidene)-3-phenyl-1-indanone (LI) respectively.



(LI)

The quaternary salts of nitrogen-containing pseudoazulenes are obtained by the quaternisation of the corresponding heterocyclic bases with alkyl halides or tosylates in aprotic solvents.[28,45,51–53,60] Despite the tautomerism of the base (LII) [the isomers (LIIa–c) are possible], alkylation results in a good yield of the quaternary salts (LIII) (the *C*-alkylation products were detected only in trace amounts). Alkaline deprotonation of the quaternary salts (LIII) leads to the pseudoazulenes (LIV):



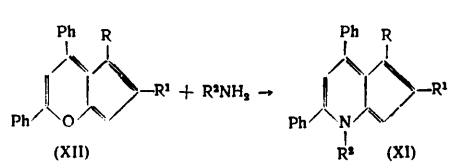
(LIIIa) (LIIb) (LIIc)

(LIIa) (LIIIb)

(LIV)

Thus the majority of the pseudoazulene systems investigated can be obtained by the deprotonation of the corresponding heteronium salts, with the exception of systems of the [c]-series. The deprotonation of certain salts takes place even in the presence of water, while for others solutions of sodium acetate or alkali are employed, depending on the basicity and stability of the final products. The yields of the nitrogen-containing pseudoazulenes are 60–80% and those of the oxygen-analogues are about 90%.

The reactions involving the direct substitution of the heteroatoms in the pseudoazulene systems must also be considered, since they permit the direct transition from, for example, oxalenes to pyrindines:[51,53,55,61,62]



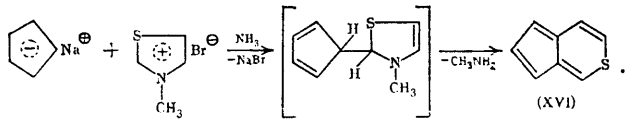
(XII) (XI)

After brief heating of compound (XII) with an excess of aniline, benzylamine, or butylamine in dimethylformamide (DMF), 1-substituted-1*H*-pyrindines (XI) were obtained in good yields.[51–53] If pyrylium perchlorates corresponding to the pyrans (XII) are introduced into the reaction, then the pyrans (XII) are formed as intermediates under the reaction conditions. A decisive factor for the successful occurrence of the reaction is evidently the high boiling point of DMF since, on heating to the boiling point in 10% alcoholic solution of ammonia,[47,58] and also on heating in ethanol with amines, compounds (XII) remain unchanged. Oxalenes, having an oxygen atom linked directly to the aromatic ring, cannot be converted in this way into nitrogen-containing pseudoazulenes. The attempts to convert 5,6-benzoxalene (XXIV) into 4*H*-cyclopenta[*b*]quinoline (XXIII) were unsuccessful (only polymeric products of the condensation of the initial compound were obtained[51,55]).

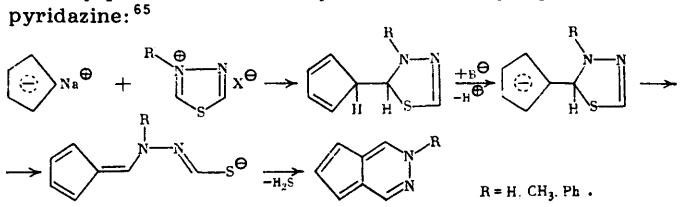
### 4. Other Methods of Synthesis

Apart from those described above, there exist several more methods of synthesis of pseudoazulenes. Although these are not quite so common, they can be used successfully in certain cases.

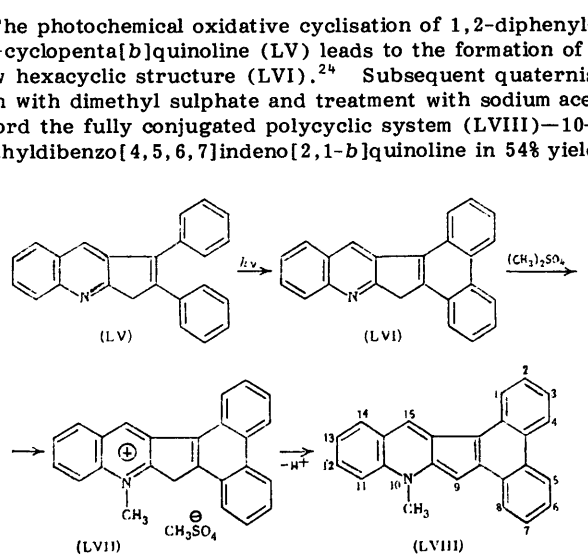
Analogously to the synthesis of the azulene by the Hafner method, the cyclopentadienyl anion can be used to obtain cyclopenta[*c*]thiapyran:[63,64]



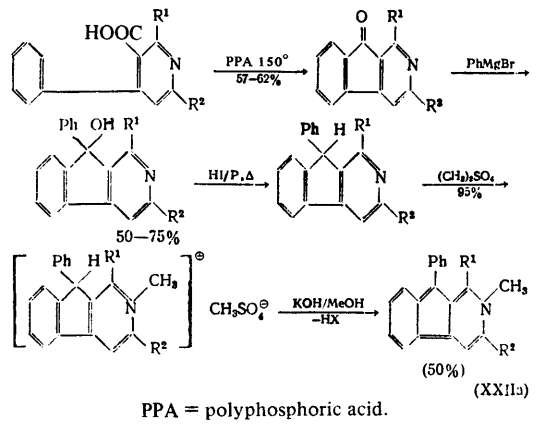

The yield of compound (XVI) is only 10%, but this method actually consists of only a single stage. So far, it has been the only procedure for the synthesis of 2*H*-cyclopenta[*d*]-pyridazine:[65]




The photochemical oxidative cyclisation of 1,2-diphenyl-3*H*-cyclopenta[*b*]quinoline (LV) leads to the formation of a new hexacyclic structure (LVI).[24] Subsequent quaternisation with dimethyl sulphate and treatment with sodium acetate afford the fully conjugated polycyclic system (LVIII)—10-methyldibenzo[4,5,6,7]indeno[2,1-*b*]quinoline in 54% yield:

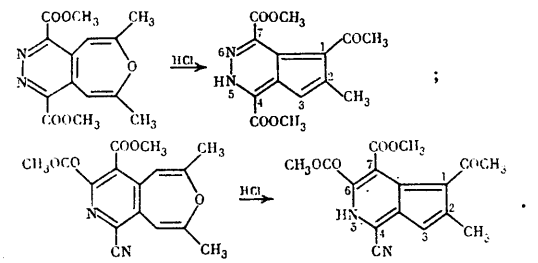



The synthesis of the 2*H*-indeno[2,1-*c*]pyridine derivative (XXIIa) has been described:[66–68]




PPA = polyphosphoric acid.

On treatment with HCl, oxepinopyridazine and oxepinopyridine derivatives are capable of rearranging to the corresponding pseudoazulenes—5*H*-cyclopenta[*d*]pyridazine and 5*H*-cyclopenta[*c*]pyridine:[69]



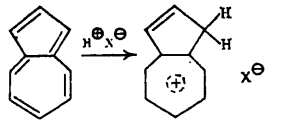

## III. CHEMICAL PROPERTIES

The reactivity of pseudoazulenes has so far been inadequately investigated and information concerning the behaviour of many systems in chemical reactions is totally lacking. Data conerning the preferred reaction centres, obtained as a result of quantum-chemical calculations, are examined below. The examples of reactivity known at present are in the main consistent with these theoretical data and indicate a rigorous analogy with the properties of azulene. The enhanced electron density in the five-membered ring and the electron deficiency of the atoms of the heterocycle are responsible for the high reactivity of the former and the passivity of the latter with respect to electrophiles. Like azulene, pseudoazulenes readily form π-complexes with various π-acids: trinitrobenzene, picric acid, etc.

The trinitrobenzene complexes are frequently used for the purification, identification, and isolation of unstable pseudoazulenes, since such complexes readily decompose into their components during chromatography on alumina. Trinitrobenzenates are sometimes introduced into electrophilic substitution reactions,[70] the insoluble trinitrobenzene being subsequently readily removed.

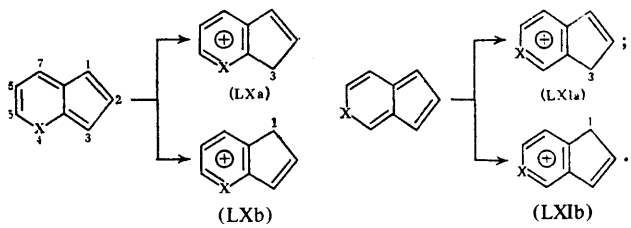
### 1. Basicity

The high basicity of azulene is responsible for the formation of the azulenium salt (LIX) on treatment with concentrated inorganic acids:[32,33,71]



(LIX)

Pseudoazulenes give rise to analogous cations, but there is in this instance a possibility of the formation of two tautomeric forms (LXa, b), because the presence of the heteroatoms disturbs the molecular symmetry. The choice between these cations is of fundamental importance for the establishment of the structure of the salts formed and their derivatives and for the elucidation of the influence of the heteroatom on the electron density of the atoms in the five-membered ring:

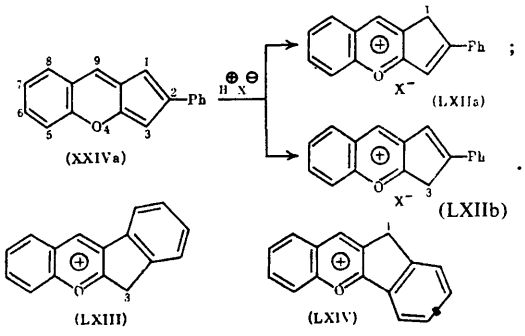


(LXa) (LXIa)

(LXb) (LXIb)

According to Anderson and Harrison,[72] the [c]-series compounds (X = S) can be protonated in both 1- and 3-positions, but the latter pathway is preferred and for this reason the cation (LXAa, X = S) is usually formed. In the [*b*]-series compounds (X = O or NR) protonation takes place exclusively in the 1-position.[51,57,58,73]

$^1$H NMR data for the pyrylium salts (LXII) have been compared[57] with the corresponding data for the salts (LXIII) and (LXIV) and it was concluded, on the basis of the study of the chemical shifts of the methylene protons (in solution in $CF_3$. .COOH) in these compounds, that the protonation of 2-phenylcyclopenta[*b*]chromene (XXIVa) proceeds exclusively in the 1-position with formation of the cation (LXIIa):



(XXIVa) (LXIIa)

(LXIIb)

(LXIII) (LXIV)

The majority of pseudoazulenes are stronger bases than azulenes. The p$K_a$ of the individual pseudoazulenes has been reported in a review[22] (the p$K_a$ of unsubstituted azulene is 1.7). Phenyl-substituted 1*H*-pyrindines (XI) and *N*-methylcyclopenta[*b*]quinolines (XXIII) are protonated even by acetic acid, i.e. their p$K_a$ exceeds 4.5.[51]

The basicities of azulenes and pseudoazulenes are usually characterised by the partition coefficient $K_\nu$:[32]

$$K_\nu = \frac{\text{pseudoazulene concentration in an inert solvent}}{\text{pseudoazulene concentration in aqueous acid}}$$

The partition coefficient $K_\nu$ has been measured as a function of the Hammett acidity function $H_0$ of the aqueous layer. In order to determine the basicity, it is necessary to select the value of $H_0$ for which the coefficient $K_\nu$ becomes unity. The Hammett acidity function $H_0$ ($K_\nu$ = 1) has been measured spectrophotometrically for certain pseudoazulenes containing various heteroatoms.[28] Nevertheless, we assume (in conformity with the data of Weiss and Schoenfeld[74]) that the basicities of these compounds can be determined from the value of $H_0$ only approximately owing to the different solubilities in the organic solvents of the compounds being compared. For this reason, the $H_0$ ($K_\nu$ = 1) values can be used only to demonstrate approximately that nitrogen-containing pseudoazulenes are much more basic than oxygen- or sulphur-containing analogues and that the basicity of pseudoazulenes is higher than that of azulenes.

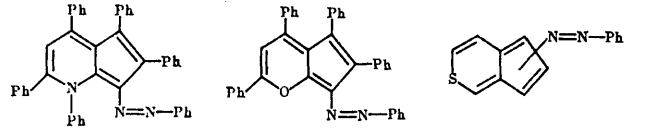
Quantitative data for the reactivities of azulenes and pseudoazulenes in relation to electrophiles have been obtained by measuring the rate of exchange of active hydrogen atoms (in the 1- and 3-positions in both azulene and pseudoazulenes) for deuterium in an acid medium.[74] The rate constant for the exchange in azulenes is lower than in 2,3; 5,6-dibenzoxalene and *N*-methyl-2,3; 5,6-dibenzopyrindine. The authors note that the rates of H–D substitution, measured in a dilute solution of $CH_3COOD$ in $CH_3OD$ for these pseudoazulenes as well as certain azulenes, correspond to the reactivities of these compounds predicted by Borsdorf on the basis of the π-electron densities calculated by the MO-LCAO method (see Section IV).

## 2. Electrophilic Substitution Reactions

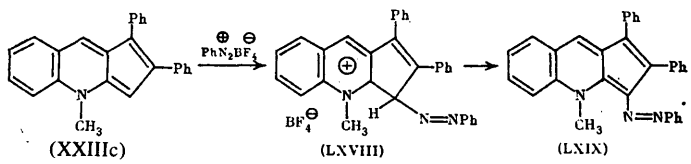
Electrophilic substitution in pseudoazulenes takes place exclusively in the 1- and (or) 3-positions (in the five-membered ring), i.e. is completely analogous to the substitution in azulenes. If both these positions in the five-membered ring are free, then in the majority of cases mixtures of mono- and di-substituted products are obtained and can be separated only by prolonged operations; the predicted preferred sites to which the reactions are directed have not been demonstrated in practice. In the majority of instances, the reactions were carried out using compounds having individually only the 1- or 3-position free. Disubstituted products have been mainly obtained for other compounds.

*(a) Azo-coupling.* Among inactivated aromatic benzenoid compounds, there are only a few substances capable of entering into the azo-coupling reaction with diazonium salts, whereas for azulenes this reaction is facilitated by the low localisation energy for electrophilic attack in the 1(3)-position. All the azulenes investigated hitherto readily give rise to azo-dyes.[33]

The pseudoazulenes (XIa), (XIIa), (XVI), and (XXIIIb, c) are smoothly coupled to benzene- and *p*-nitrobenzene-diazonium fluoroborates in acetonitrile[51] or in a dioxan–ethanol mixture.[58] Quaternary salts, for example (LXVIII), are formed in the first stage and on treatment with a base (sodium acetate) are converted into azo-compounds in 70–90% yield:



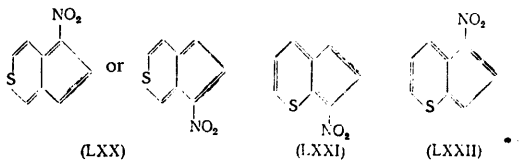
(LXV) from (XIa) (LXVI) from (XIIa) (LXVII) from (XVI)



(XXIIIc) (LXVIII) (LXIX)

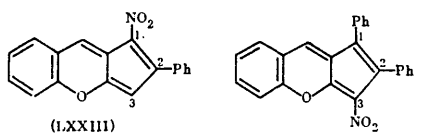
Azo-dyes of the type (LXIX) have the azo-group in the 3-position, while in 2-phenylcyclopenta[*b*]quinoline (XXIIIb) the azo-group can enter the 1- or 3-position. Indeed, two structurally isomeric azo-dyes have been obtained on azo-coupling, which has been demonstrated by thin-layer-chromatography (TLC); but the isomers could not be separated by crystallisation.[51]

*(b) Nitration.* As a result of the sensitivity of pseudoazulenes to strong acids and oxidants, they cannot be nitrated by the nitrating mixture, but nitration can be readily achieved by treatment with $Cu(NO_3)_2$ in acetic anhydride or with tetranitromethane in pyridine.[26,33,34,50,61,72,75] Only mononitro-derivatives of pseudoazulenes are known; the attempts to obtain dinitro-derivatives by treatment with an excess of tetranitromethane in pyridine and also with copper or silver nitrate in acetic anhydride were unsuccessful.[72] The synthesis of nitropseuduazulenes has been described: 3-nitro-1,2,5,7-tetraphenylcyclopenta[*b*]pyran and 3-nitro-1,2;5,6-dibenzoxalene as well as 1(3)-nitrocyclopenta[*c*]thiapyran (LXX).[61,72] It has been noted that the properties of the product (LXX) preclude a choice between the structures of the 1- and 3-substituted derivatives:



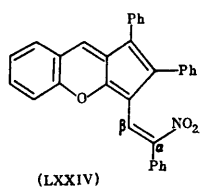
(LXX) (LXXI) (LXXII)

On nitration with an excess of tetranitromethane in pyridine, cyclopenta[*b*]thiapyran (XIII) affords two isomeric products (LXXI) and (LXXII), whose structures have not been determined unambiguously. However, it has been established that the reaction of 2-phenylcyclopentachromene (XXIVa) with $C(NO_2)_4$ in pyridine leads exclusively to the 1-nitro-derivative (LXXIII), while the 1,2-diphenylcyclopentachromene is nitrated, as expected, in the 3-position:[75]



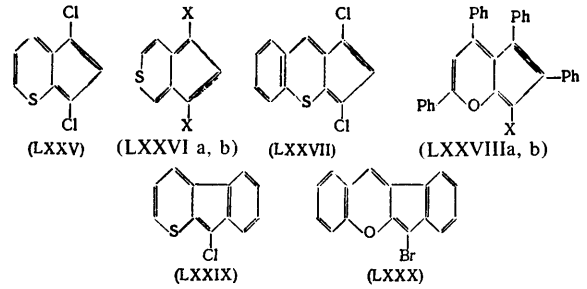
(LXXIII)

The 3-*trans*-styryl derivative of 1,2-diphenylcyclopentachromene is capable of being nitrated at the α-carbon atom of the styryl residue, i.e. in the position most remote from the cyclopentachromene ring and at the same time conjugated with it (the vinylogy principle),[76] forming the nitrostyryl derivative (LXXIV):



(LXXIV)

*(c) Halogenation.* The best halogenating agents for azulenes[33] and pseudoazulenes are *N*-halogenosuccinimides, whose use makes it possible to obtain mono- and di-halogeno-derivatives in high yields (up to 82%).[26,34,38,50,58,61,72]



(LXXV) (LXXVI a, b) (LXXVII) (LXXVIIIa, b)

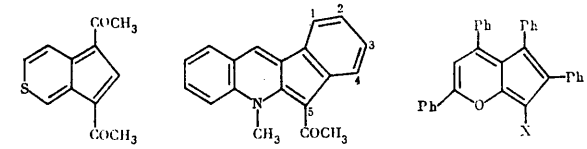
(LXXIX) (LXXX)

a: X=Cl
b: X=Br

The halogenation of pseudoazulenes without substituents in the 1- and 3-positions yielded the disubstituted products (LXXV),[34] (LXXVIa,b),[61,72] and (LXXVII).[38] The monosubstituted pseudoazulenes (LXXVIIIa, b),[58] (LXXIX),[34] and (LXXX)[26,50] have also been obtained with the aid of *N*-halogenosuccinimides. The attempt to obtain the trichloro-derivatives from cyclopenta[*c*]thiapyran (LXXVIa) leads only to a polymeric material,[72] while 1,3-dichloroazulene is capable of being chlorinated by *N*-chlorosuccinimide with formation of 1,3,5-trichloroazulene in 17% yield.[77]

*(d) Acylation and formylation.* It is known that azulenes are acylated by carboxylic acid chlorides in the presence of aluminium chloride, perchloric acid, or tin tetrachloride with formation of 1-mono- and 1,3-di-acyl derivatives. The reaction with $(CF_3CO)_2O$ takes place almost quantitatively without a catalyst.[33] Azulene has been acylated with the chlorides or bromides of oxalic, malonic, and phenylacetic acids.

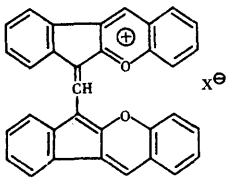
However, none of these methods are very applicable to pseudoazulenes owing to their greater basicity and lower chemical stability. 1,3-Diacetylcyclopenta[*c*]thiapyran (LXXVIc) has been obtained in only 9% yield by the acylation of compound (XVI) with acetic anhydride in the presence of $SnCl_4$:[61,71]



(LXXVIc) (XXVIIId) (LXXXI): X = CHO

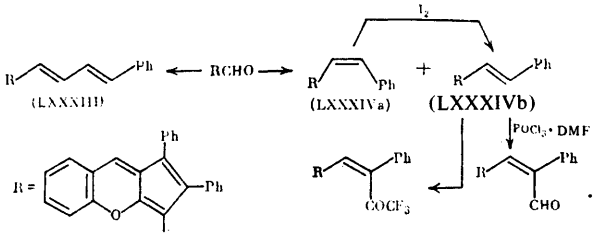
5-Acetyl-*N*-methyl-1,2;5,6-dibenzoazalene (XXVIIId) has been obtained by reaction with acetic anhydride without a catalyst.[52] The Vilsmeier–Hack reaction is most often employed to synthesise formyl derivatives.[26,50,52,58] Both mono- and di-formylazulenes have been obtained from azulenes by this method.[33] The aldehyde (LXXVI) has been obtained by formylating compound (XIIb) by the complex $POCl_3$.DMF with isolation of the intermediate phosphorodichloridate [X = CH = $N^+(CH_3)_2.PO_2Cl_2^-$] in a high yield. The 1,3-dialdehyde has been obtained in 70% yield by heating 2-phenylcyclopentachromene with an excess of the Vilsmeier reagent.[75] The thermal acylation of compound (XXIVa) with malonic acid in the absence of solvents leads to the 1-acetyl derivative.[78] Under mild conditions (treatment with oxalyl bromide in $CCl_4$ for many days at 20 °C), the pseudoazulenes (XIII), (XXVIII), and (XXIX) form substituted glyoxylic acids, which are decarbonylated to the corresponding carboxylic acids on heating to 70 °C.[79,80] It has been shown[26,52] that a high basicity and ready hydrolytic elimination of the formyl group on heating in the presence of

inorganic acids are characteristic of pseudoazulene aldehydes.[26,52] 3-Formyldibenzoxalene in alcoholic solutions[26] splits off the formyl group in the presence of $POCl_3$ and affords the intensely green dioxalenylmethane derivative (LXXXII) ($\lambda_{max}$ = 722 nm, lg ε = 4.42 in methanol).

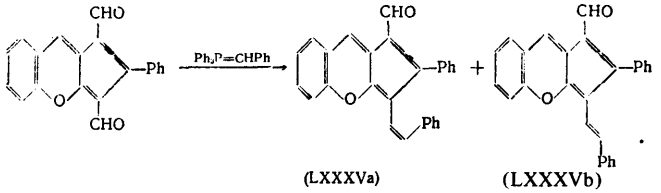


(LXXXII)

The same compound can be obtained from dibenzoxalene and 3-formyldibenzoxalene, analogously to the synthesis of the diazulenylmethane dye obtained by condensing azulene with 1,4-formylazulene.[33] Pseudoazulene aldehydes can be used for the synthesis of other derivatives, for example, polyene derivatives. Thus a series of styrylpseudoazulenes have been obtained by the Wittig reaction[76] from mono- and di-formylcyclopentachromenes. The virtually pure *trans*, *trans*-isomer (LXXXIII) has been obtained by reaction with cinnamylidenephosphorane, while the reaction with benzylidenephosphorane produced the *cis*- and *trans*-isomers (LXXXIVa,b) in proportions of approximately 1 : 2. The *cis*-isomer (LXXXIVa) is converted quantitatively into the *trans*-isomer on treatment with catalytic amounts of $I_2$ by analogy with the isomerisation of *cis*-1-styrylazulene:[81,82]



Compound (LXXIVb) can undergo the electrophilic substitution reaction in the CH=CH–Ph side group (in the α-position in the styryl residue). The increased electron density at the C(1) atom of the 2-phenylcyclo pentachromene system affects the structural selectivity of the Wittig reaction for the 1,3-dialdehyde, which reacts with one equivalent of $Ph_3P$=CHPh to produce the *cis*- and *trans*-3-styrylaldehydes (LXXVa) and (LXXXVb):

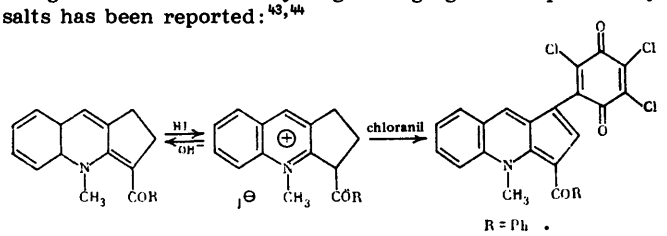


(LXXXVa) (LXXXVb)

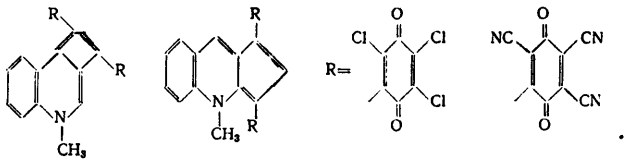
*(e) Reactions with organic π-acids.* The reaction of 7,7,8,8-tetracyanoquinodimethane (TCQD) with azulenes leads to the formation of products of the 1,6-addition to the quinonoid bond system of TCQD as a result of the initial one-electron oxidation of the donor by the acceptor,[83] exactly as in the reaction of azulenes with tetracyanoethylene.[84,85]

Pseudoazulenes also readily form π-complexes with various acids: trinitrobenzene, picric acid, etc.[7,14,27,32,33] The complexes with trinitrobenzene are frequently used to purify, identify, and isolate unstable pseudoazulenes; these complexes readily decompose into their components in chromatography.

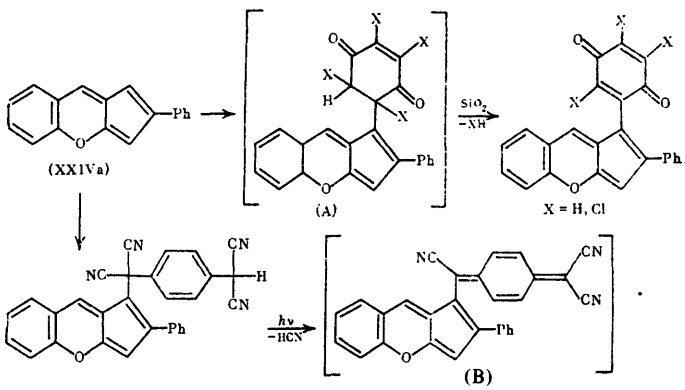
The formation of 1-(3,5,6-trichloro-1,4-benzoquinon-2-yl)-3-benzoyl-4-methyl-4*H*-[*b*]quinindine in 64% yield using chloranil as the dehydrogenating agent for quaternary salts has been reported:[43,44]



The following disubstituted derivatives were later obtained on dehydrogenation of the quaternary salts of hydrogenated pseudoazulenes:[29,45,46]



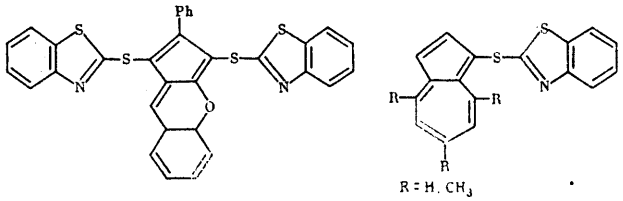
The high reactivity of the 1-position in compound (XXIVa) enables it to participate in reactions involving addition to organic π-acids, for example, to benzoquinone, chloranil, and TCQD, with the ultimate formation of products resulting from the substitution of hydrogen, chlorine, or a CN group. However, the products (A) and (B) proved to be unstable and could not be isolated in a pure state:[86]



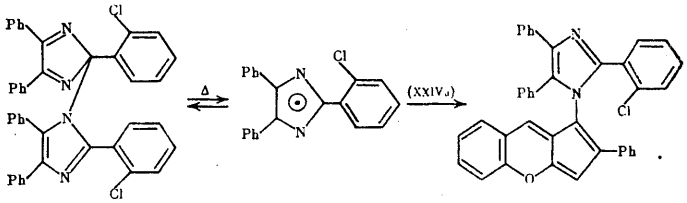
## 3. Homolytic Substitution

The majority of radical substitution reactions have been thoroughly investigated for azulene derivatives.[31–33,87] Pseudoazulenes, which are no less reactive than azulenes, should also enter into similar reactions, but the literature data on this topic are extremely limited.[22] It is known only that radical species such as 2-benzothiazolylsulphenyl, 2-(*o*-chlorophenyl)-4,5-diphenylimidazolyl, and 2,6-diphenyl-4*H*-4-pyranyl, formed at elevated temperatures, react with compound (XXIVa).[88] When the latter is fused with 2,2-dibenzothiazolyl disulphide (at 200 °C), 1,3-di(benzothiazolylthio)cyclopenta[*b*]chromene is formed in 12% yield; the formation of the mono-substituted benzothiazolylthio-derivative was not then observed, while in the reactions with azulene

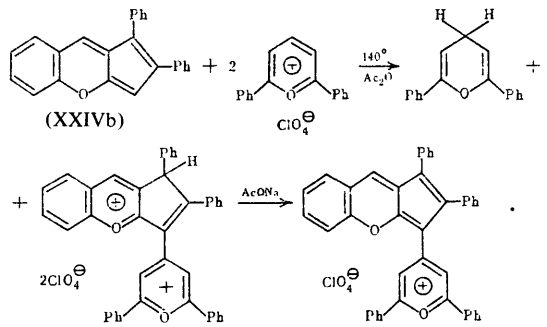
and 4,6,8-trimethylazulene, only the 1-substituted derivatives were obtained:[89]



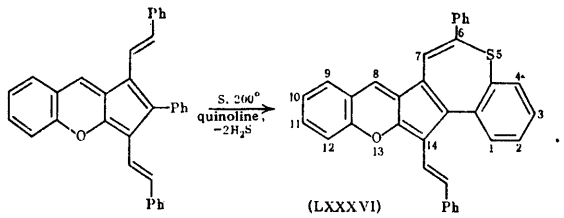
The thermal reaction of 1,2-bis[2-(*o*-chlorophenyl)-4,5-diphenylimidazolyl] with 2-phenylcyclopenta[*b*]chromene leads to the formation of the 1-substituted derivative, as in the reaction with azulene:[90]



The reaction of compound (XXIVb) with 2,6-diphenylpyrylium perchlorate in boiling acetic anhydride leads to the formation of 2,6-diphenyl-4-{1,2-diphenylcyclopenta[*b*]-3-chromylia}pyrylium diperchlorate in 75% yield.[91] It has been suggested that the primary step in this reaction is the one-electron oxidation of the substrate by the 2,6-diphenylpyrylium cation, which leads to the formation of the extremely reactive 1,2-diphenylcyclopenta[*b*]chromenylium radical-cation and the 2,6-diphenyl-4*H*-4-pyranyl radical, which recombine to a doubly charged primary cation:

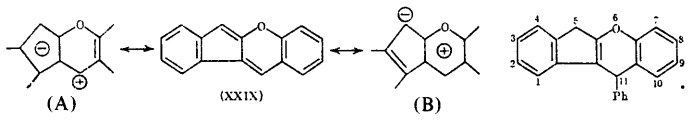


An analogous reaction has been carried between 2,6-diphenylpyrylium perchlorate and 6-heterylazulenes.[92] Other organic compounds with an enhanced electron density at, at least, one of the carbon atoms (*NN*-dimethylaniline[93,94] and 1-methyl and 2-methyl-indoles[95,96]) or substances capable of being readily oxidised to readily stable radical-cations (ferrocene[97]) can also serve as substrates in this reaction. An example of the transmission of the influence of the electron density to the non-benzenoid aromatic ring on the reactivity of the conjugated side chain (vinylogy) is provided by the reaction of 2-phenyl-1,3-distyrylcyclopentachromene with sulphur, which leads to a new heterocyclic system: 6-phenyl-14-styrylbenzo[2',3']thiepino[4',5';2,1]cyclopenta-[*b*]chromene (LXXXVI) in 40% yield:[76]

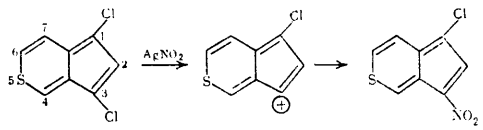


## 4. Nucleophilic Substitution

The effect of alkyl- and aryl-lithium has been investigated on the pseudoazulene systems (XVIII), (XXIV) and (XXIX).[16,45,46] The hydrocarbon residue then attacks the carbon atom located opposite to the heteroatom. Dihydrocompounds, which can be again dehydrogenated to pseudoazulenes, are obtained by hydrolysing the intermediates. Such reactions are characteristic of π-deficient heterocycles. The system (XXIX), which is isoelectronic with azulene, can be described as a hybrid of resonance structures—those of the pyrylium cation (B) and the anion (A):



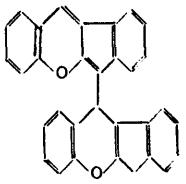
The limiting form (A) is responsible for the sensitivity of dibenzoxalene (XXIX) to nucleophiles, which has been conformed by its reaction with phenyl-lithium, leading to 11-phenyl-5,11-dihydrodibenzoxalene. Dibenzoxalene (XXIX) is resistant to lithium malonate and maleic anhydride; the attempts to replace the oxygen heteroatom by sulphur and nitrogen proved unsuccessful.[26] It is also known that only one chlorine atom, located at the C(3) atom, in 1,3-dichlorocyclopenta[*c*]thiapyran is substituted by silver nitrite:[72]



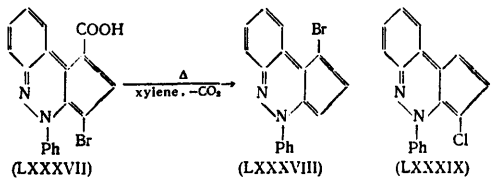
## 5. Other Reactions of Pseudoazulenes

Apart from the reaction described above, isothialene (XVI) has been substituted by thiocyano-groups using thiocyanogen, which led to 1,3-dithiocyanocyclopenta[*c*]thiapyran.[61,72] The reaction with $Cu(SCN)_2$ in acetonitrile yielded 1,2-diphenyl-3-thiocyanocyclopenta[*b*]chromene,[98] while that with $Cu(SO_2Ph)_2$ afforded benzenesulphonyl derivatives of 1,2-diphenyl- and 2-phenylcyclopenta[*b*]chromene.[75]

The alkylation of 1,2,5,7-tetraphenylcyclopenta[*b*]pyran with t-butyl chloride in the presence of aluminium chloride has been carried out successfully.[58] Inorganic acids and phosphoryl chloride induced the dimerisation of dibenzoxalene (XXIX) with formation of a dimer having the following structure:[53]



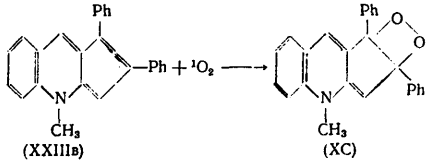
An instance of allylic rearrangement has been described in relation to 4-phenyl-4*H*-cyclopenta[*c*]cinnoline.[99] On being refluxed in xylene, 3-bromo-4-phenyl-4*H*-cyclopenta[*c*]-cinnoline-1-carboxylic acid (LXXXVIII) is decarboxylated with a simultaneous rearrangement, leading to the formation of the bromo-derivative (LXXXVIII):




(LXXXVII) (LXXXVIII) (LXXXIX)

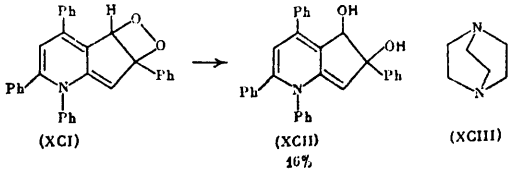
In contrast to the bromoacid (LXXXVII), the corresponding chloroacid is decarboxylated under the same conditions without a rearrangement, forming the chloro-derivative (LXXXIX). It is noteworthy that the decarboxylation of the bromoacid (LXXXVII) leads only to the bromo-derivative which can be obtained by brominating 4-phenyl-4*H*-cyclopenta[*c*]cinnoline by *N*-bromosuccinamide.

The photosensitised pseudoazulene oxidation processes have been examined.[100] Polyarylcyclopenta[*b*]quinolines, for example, compound (XXIIIc), 1-pyrindines (XI), and cyclopenta[*b*]chromenes sensitise the formation of singlet oxygen on irradiation in air in various solvents and are oxidised by it to dioxetans, which readily decompose with chemiluminescence. Dioxetans also generate $^1O_2$, as a result of which the oxidation reactions undergo self-acceleration:




(XXIIIb) (XC)

The formation of the dioxetan having the structure (XC) has been suggested. The thermal decomposition of the dioxetan (XCI) leads to dihydroxy-compound (XCII):

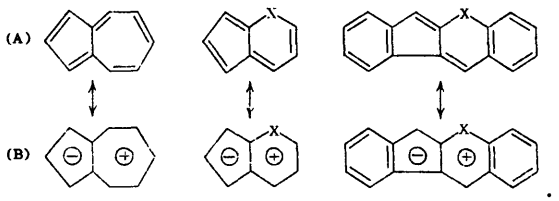



(XCI) (XCII) 16% (XCIII)

The photodecolorisation is retarded in the presence of a typical $^1O_2$ quenching agent—diazabicyclo-octane (XCIII), or a chemical quenching agent—2,5-dimethylfuran, which forms a peroxide. The quantum yields in the decomposition of pseudoazulenes are approximately $2 \times 10^{-3}$.

## IV. QUANTUM-CHEMICAL CALCULATIONS

The aromaticity of pseudoazulenes is determined by the sextet of π-electrons in the heterocyclic ring, made up of the single unshared electron pair of the heteroatom, located in the *p* orbital axial in relation to the plane of the ring, and four π-electrons of the double bonds. The aromatic sextet of electrons in the five-membered ring is obtained as a result of the possibility of polarisation in the direction from the six-membered ring to the five-membered ring, the conditions in both rings approaching those of an aromatic sextet. For this reason the dipolar structure makes a significant contribution to the electronic structure of pseudoazulenes. The azulene[32] and pseudoazulene[35,38] systems can be represented by resonance hybrid structures, intermediate between the Kekulé form (A) and the dipolar form (B).



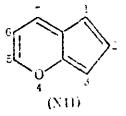

The data for electron distribution obtained for pseudoazulenes by the LCAO-MO method in terms of the Hückel approximation[57,101–110] and by the Pariser–Parr–Pople (PPP) method,[98,101] the reactivity data, and the electronic absorption spectra indicate an azulene-like behaviour of representatives of this class of non-benzenoid non-alternant aromatic compounds. Despite the difficulties associated with the allowance for the contribution by polar structures, the electron deficiency in the six-membered ring and the excess electron density in the five-membered ring have been calculated for all the pseudoazulenes. It follows from the molecular diagram for indolizine that a considerable positive charge is localised on the nitrogen atom and that there is a negative charge on all the carbon atoms except the C(8) atom (six-membered ring).[112] Since different workers have used different sets of parameters, the calculated electron density distributions on the carbon atoms could not be compared directly. The results yielded by the same set of parameters for different systems lead to the following conclusions: the electron density on the carbon atoms decreases from the nitrogen-containing pseudoazulenes to the oxygen-containing compounds as a consequence of the greater electronegativity of oxygen. In the [*b*]-series of pseudoazulenes the carbon atoms of the five-membered ring have a higher electron density than for the [*c*]-series. The presence of a condensed aromatic ring in the 1,2-positions increases the electron density in the five-membered ring, while condensation in the 5,6-positions reduces it. The distribution of electron density on the individual atoms of the five-membered ring is as follows: the 1- and 3-positions have an increased electron density compared with that in the 2-position. In the [*b*]-series the C(1) atom is more electron-deficient than the C(3) atom,[22,98] while in the [*c*]-series the situation changes. In azulene, the 1- and 3-positions are equivalent as a consequence of the symmetry of the molecule, while the 2-position is much more electron-deficient as in pseudoazulenes.[32] The self-consistent field calculations for the azulene molecule[113,114] yielded a somewhat different picture. On average, the five-membered ring carries an excess negative charge, as before, but, in contrast to the result yielded by the simpler Hückel MO method, the atom in the 2-position carries a positive charge.

Electrophilic substitution of non-condensed representatives of pseudoazulenes (XI)–(XVI) is directed preferentially to the 1- or 3-position. If both these positions are free, then they can be attacked simultaneously. Attack by nucleophiles should take place in the 7-position for representatives of the [*b*]-series and in the 4-positions for the [*c*]-series. Radical reactions are directed to the 5-position for the [*b*]-series, while representatives of the [*c*]-series react in the 4-position.[108] Various preferred positions for electrophilic, nucleophilic, and radical substitution reactions follow from the localisation energies $A_r$, the π-electron densities $q_r$, or the free valence indices $F_r$ for the individual C atoms. The reactivities of the C atoms of cyclopenta[*b*]pyran (XII) are presented in Table 2.[104]

**Table 2.** Preferred mode of substitution in the oxalene (XII)*.

| Electrophilic substitution | | Nucleophilic substitution | | Radical substitution | | Electrophilic substitution | | Nucleophilic substitution | | Radical substitution | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $A_r^{\oplus}$ | $q_r$ | $A_r^{\ominus}$ | $q_r$ | $A_r^{\odot}$ | $F_r$ | $A_r^{\oplus}$ | $q_r$ | $A_r^{\ominus}$ | $q_r$ | $A_r^{\odot}$ | $F_r$ |
| 1 | 3 | 5 | 5 | 5 | 5 | 5 | 6 | 1 | 2 | 3 | 3 |
| 3 | 1 | 7 | 7 | 1 | 7 | 6 | 7 | 3 | 1 | 2 | 2 |
| 2 | 2 | 2 | 6 | 7 | 1 | 7 | 5 | 6 | 3 | 6 | 6 |

*The reactivity diminishes on moving towards lower rows.



(XII)

It follows from the calculations of the electronic absorption spectra by the Hückel MO method[101,102,104,107] and the PPP method[98,111] that, analogously to azulenes, the long-wavelength band in the range 500–700 nm corresponds to the $S^0 \rightarrow S^1$ transition, while the band in the range 360–390 nm corresponds to the $S^0 \rightarrow S^2$ transition. The absorption in the short-wavelength part of the spectrum is determined by complex transitions. The long-wavelength transition is accompanied by charge transfer preferentially from the five-membered ring to the six-membered heterocycle. Thus the overall negative charge on the atoms of the five-membered ring in 2-phenylcyclopentachromene is reversed on transition to the first excited state (+0.096 against −0.374 in the ground state), while that in the heterocycle diminishes appreciably (to +0.008 against +0.315). The bonds in the rings become to a large extent equalised. The comparatively low intensity of the band can be accounted for by the small change in the dipole moment of the transition ($\Delta\mu$ =0.40 D). Theoretical analysis of the long-wavelength electronic transition has shown that it is determined mainly by the fulvene group, which is a constituent fragment of the pseudoazulene molecule.[98]

It has been demonstrated theoretically[52,111] that the influence of the heteroatom on the absorption spectra of heterocyclic pseudoazulenes is very insignificant. According to a quantum-chemical calculation, the influence of substituents on the energy of the long-wavelength transition is the same as that for azulenes.[108] A bathochromic or hypsochromic shift of the long-wavelength band, induced by the introduction of alkyl groups in different positions in the azulene ring (the Plattner rule), is especially typical for azulenes.[115] The influence of the methyl group in different positions in cyclopenta[*c*]pyran has been calculated[102] and it has been shown that the Plattner rule should hold also for pseudoazulene systems. Inadequate experimental data make it impossible to confirm this postulate.

## V. PHYSICOCHEMICAL PROPERTIES

### 1. Stability

Pseudoazulenes are in most cases deeply coloured, crystalline, weakly basic compounds, which dissolve in aqueous solutions of strong acids with loss of the characteristic colour and are reprecipitated unchanged on dilution with water or aqueous bases and can thus be extracted from organic solvents. In terms of their colour, basicity, and resistance to alkalis, they resemble azulene. In contrast to the majority of azulenes, numerous pseudoazulenes are unstable. Simple unsubstituted representatives of certain systems cannot be isolated in a pure form at all. Phenyl substituents stabilise the system and polyaryl-substituted compounds can be stored for a long time at room temperature without appreciable decomposition. Thus *N*-methyl derivatives of unsubstituted 1-pyrindine,[58] cyclopenta[*b*]quinoline,[45,46] and indeno[1,2-*b*]-pyridine[27] are unstable, while 1-phenyl and 1,2-diphenyl-cyclopenta[*b*]quinolines as well as the tri- and tetra-phenyl derivatives of 1-pyrindine are comparatively stable.[51] Substitution by even one strong electron-accepting substituent is sufficient to achieve the complete stabilisation of the unstable systems. "Picrylation" has an especially powerful stabilising effect.[116] The stability decreases very markedly on passing from sulphur- and nitrogen-containing systems to the oxygen analogues; thus cyclopentathiapyran and 2*H*-pyrindine were synthesised a long time ago,[36,37] while cyclopentapyran is still unknown. The [*c*]-series pseudoazulene systems are more stable than compounds of the [*b*]-series. Cyclopenta[*b*]thiapyran has been isolated in the form of an extremely unstable blue oil;[15] in contrast to this, cyclopenta[*c*]thiapyran[43] is a fairly stable crystalline substance. Under the influence of atmospheric oxygen and light, many pseudoazulenes decompose very rapidly. Solutions in non-polar solvents are preserved for a long time, while in polar solvents, especially in methanol, decomposition is observed over a period of 4–5 h.[51] The stability of pseudoazulenes in relation to bases makes it possible to chromatograph them on alumina.

### 2. Electronic Absorption Spectra

There is no doubt that the long-wavelength absorption, observed for azulene in the region of approximately 600 nm, is most characteristic for the identification of the compounds considered. Only an indirect comparison of the spectra of pseudoazulenes with those of carbocyclic analogues is possible, since the corresponding polyphenylazulenes and certain polycyclic condensed systems are so far unknown, while many pseudoazulene systems without substituents are unstable. The electronic spectra of 1,2-, 4,5-, and 5,6-benzoazulenes have been compared with those of unsubstituted azulenes.[117–125] Since azulenes phenyl-substituted in the seven-membered ring have the same absorption spectrum as unsubstituted azulenes,[126,127] El'tsov et al.[51] compared the spectra of pyrindines with those of 2-phenylazulene.[128] The comparison showed that the long-wavelength band in the spectra of non-condensed 1-pyrindines has undergone a hypsochromic shift by 60–70 nm compared with

the spectra of azulene. Substituents at the nitrogen atom have little influence on the long-wavelength transition and hardly affect the short-wavelength transitions. Pyrindines absorb in approximately the same part of the spectrum as the corresponding oxygen analogues. The influence of phenyl substituents on the direction and magnitude of the shifts of the absorption maxima[16,27,28,48,57] is approximately the same as for azulene. The phenyl group in the 1- or 3-position in cyclopenta[*b*]quinoline induces a 22 nm bathochromic shift (there is a 26 nm shift in the spectrum of azulene[128]). In the oxygen analogue—2-phenylcyclopenta-[*b*]chromene—the successive introduction of phenyl substituents into the five-membered ring leads to a bathochromic shift of the long-wavelength band by 42 nm for one phenyl group (the calculated shift is thus 28.2 nm) and by 60 nm for two such groups. The *trans*-styryl group in the 1-position induces a +80 nm shift, while that in the 3-position induces a 60 nm shift. Two *trans*-styryl groups cause a "red" shift by 140 nm without an appreciable change in the oscillator strength.[98] Electron-accepting substituents in the five-membered ring of 4*H*-indeno[2,1-*b*]quinoline cause a hypsochromic shift of the absorption by 30–35 nm, while in the spectrum of the oxygen analogue the shift is by only 5–10 nm.[52] The introduction of electron-accepting substituents in the 3-position in 1,2-diphenylcyclopenta[*b*]-chromene results in a hypsochromic shift of the long-wavelength band by approximately 30 nm with an increase of the oscillator strength by a factor of 1.5. The same substituents in the 1-position induce a 10–30 nm bathochromic shift and an increase of the oscillator strength of the band by a factor of 4–5,[98] in contrast to azulene, where a hypsochromic shift is observed exclusively.[31]

The emission spectra of azulene are known to be unusual:[129–132] the fluorescence of azulene and its derivatives corresponds to a very rare $S^2 \rightarrow S^0$ type of transition. Such anomalous luminescence is probably a consequence of the marked splitting of the $S^2$ and $S^1$ levels and a greater mutual approach of the $S^1$ and $S^0$ levels than for other aromatic systems. It has been found[51,53] that the luminescence of pseudoazulenes is just as anomalous as for azulenes. The quantum yields are $10^{-4}$–$10^{-5}$ against $10^{-2}$ for azulene.[130] As for azulene, the authors did not observe phosphorescence in pseudoazulenes. The structure of the electronic spectra and the luminescence properties of 1,2-benzoxalene derivatives have been examined.[134]

### 3. Infrared, $^1$H NMR, and Mass Spectra

Virtually no systematic studies of the IR, $^1$H NMR, and mass spectra of pseudoazulenes are described in the literature. These data are usually given in the experimental parts of synthetic studies.

The IR spectra of substituted pseudoazulenes contain only insignificant characteristic bands corresponding to the normal absorption of aromatic rings. For example, the spectra of indeno[2,1-*b*]benzopyrans in the range 1560–1660 cm$^{-1}$ have four bands due to the vibrations of the aromatic ring and the C=C stretching vibrations and the moderately intense band at 1230 cm$^{-1}$ has been attributed to the $\nu$(C=O) deformation vibrations of the –C=C–O group.[26] The vibration frequencies of the substituents in the five-membered ring in both azulene and pseudoazulenes are appreciably reduced.[31,58,134,135] If the system contains the CN, CHO, or $COCH_3$ groups in the five-membered ring, then the latter, being substituents of the second kind, promote the polarisation of the system with formation of the structure (B). The $\nu$(C=O) vibration frequencies in the aldehydes (1611 cm$^{-1}$) and ketones (1598 cm$^{-1}$) derived from indeno[2,1,*b*]quinoline (XXVIII) are reduced compared with the frequencies in the similar derivatives of indeno[2,1-*b*]benzopyran (XXIX) (1631 cm$^{-1}$ in the aldehydes and 1625 cm$^{-1}$ in the ketones),[103] which can be explained by the smaller electronegativity of the nitrogen atom compared with the oxygen atom, which promotes the formation of a polar structure. In the IR spectrum of 1,3-diacetylcyclopenta[*c*]thiapyran the stretching vibrations at the carbonyl group appear at 1629 cm$^{-1}$, i.e. at longer wavelengths than the corresponding vibrations of the carbonyl group in 1,2-diacetylazulene, observed at 1638 cm$^{-1}$.[72] The dependence of the $\nu$(C=O) vibration frequency on the position of the CO group in azulene has been indicated.[136] The authors note that the spectra of 1-phenylacetyl- and 2-phenylacetyl-azulenes contain the absorption bands due to the carbonyl group at 1640 and 1675 cm$^{-1}$ respectively. In the spectra of 1-carbonyl-containing pseudoazulenes of the cyclopenta[*b*]chromene series there is a possibility of the overlap of the frequencies of the aromatic C=C and C=O bonds. The possibility of using the integral intensities of the vibration bands of the bonds and $^{13}$C NMR to demonstrate the presence of carbonyl groups has been examined.[137] $^{13}$C NMR spectrum of 1,3-diformyl-2-phenylcyclopenta[*b*]-chromene in $CDCl_3$ shows two signals with chemical shifts $\delta$ of 186.61 and 183.77 p.p.m., corresponding to the carbon atoms of the two formyl groups, and also the signals of the phenyl substituent in the region of 77.25 p.p.m. and the remaining carbon atoms at 118.27–138.86 p.p.m. A considerable upfield shift of the $^{13}$C resonance signal of the C=O group compared with acetophenone (196.9), benzaldehyde (190.7), and acetone (204.1) has been noted.[138] It follows from the comparative analysis of the shifts $\delta$ of the CHO groups in the $^{13}$C NMR spectra, the $\nu$(C=O) frequencies, and the integral intensities of the absorption bands due to the stretching vibrations of the C=O groups in the IR spectra that the CHO groups in the 1- and 3-positions in azulene and cyclopenta[*b*]chromene are strongly polarised, which is comparable to the polarisation of the C=O group in benzotropones.[139] The $^{13}$C NMR spectra of unsubstituted azulene and mono- and poly-methylazulenes have been published.[140] The chemical shifts of the methyl groups in different positions in the azulene ring are in the range $\delta$ = 12.6–28.5 p.p.m., while the shifts for the $C_1$–$C_{10}$ atoms are in the range $\delta$ = 116–146.9 p.p.m.

The $^1$H NMR spectrum of azulene[141,142] agrees well with its structure. The $^1$H NMR spectrum of cyclopenta[*c*]thiapyran has been interpreted.[61] The spectra of its methyl derivatives were examined by Radeglia and Wagner[64] and those of the 1-pyrindine system were considered by Anastassion and Reichmanis.[143] The protons in the 1-, 2-, and 3-positions in azulene are not shielded to the same extent as the corresponding protons in cyclopenta[*c*]thiapyran. It follows from this that the polar structure of pseudoazulenes has a stronger influence on the distribution of electron density in the ground state.[61] The different degrees of shielding of the individual protons in the pseudoazulene nuclei, which should be expected on the basis of calculated data as a consequence of the differences in electron density, do indeed follow from the $^1$H NMR spectra of these compounds, for example, cyclopenta[*b*]quinoline.[29,43–46] In the $^1$H NMR spectra of cyclopenta[*b*]pyrylium salts obtained by protonating cyclopenta-[*b*]pyran (XII), cyclopenta[*b*]chromene (XXIV), and indeno[2,1-*b*]chromene (XXIX) by $HClO_4$, the signal of the methylene group appears in the range $\delta$ = 4.48–4.77 p.p.m. (in $CF_3COOH$).[57] In the spectrum of the protonated form of 4,6,8-trimethylazulene (in 96% $H_2SO_4$), the signal of the $C(1)H_2$ methylene group is observed at 3.56 p.p.m. The strong deshielding influence of the electron-accepting groups $PhSO_2$, $CH_3CO$, and $CF_3CO$ in the 1-position [the substituted C(1) atom of the trimethylazulene system is protonated]

causes a downfield shift of the C(1)–H signal (5.85, 5.40, and 4.80 p.p.m. respectively).[144,145–149] 2-Alkyl derivatives of 6-, and 7-, and 8-ethoxycarbonylindolizines are protonated at the C(3) atom, the protons of the methylene group formed in this process being manifested by a signal at 5.28 p.p.m. with an intensity equivalent to two proton units. The presence of the CHO, $NO_2$, and $COCH_3$ substituents in the 3-position (in contrast to the 4,6,8-trimethylazulene molecule) alters the centre subjected to protonation, which is directed in this instance to the oxygen atom of the substituent.[150–153]

There are no literature data on the mass spectra of pseudoazulenes containing one heteroatom, although the mass spectra of compounds with several heteroatoms confirm the aromatic character of pseudoazulenes.[23,76,154,155] As for other aromatic compounds, the principal peak is identical with that of the molecular ions; the spectra contain numerous doubly charged ions; there is a small number of low-intensity fragment peaks.

### 4. The Dipole Moment

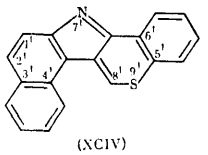
Since the five-membered ring is enriched in electrons, the azulene molecule has a dipole moment, the five-membered ring being the negative end of the dipole. The dipole moment of azulene (6.9 D) has been calculated from the electron densities and C–C bond orders; direct measurement yielded 1.04 ± 0.05 D.[156] The theoretical value calculated in terms of the simple MO-LCAO approximation differs very markedly from the above value. However, improved calculations have shown that the charge distribution in azulene is more uniform and the dipole moment is therefore appreciably smaller than the value predicted by the simple MO theory. For example, application of the MO method with allowance for configuration interaction led to 1.88 D.[157] The value closest to the experimental dipole moment (1.33 D)[158] has been obtained by the self-consistent field calculation using variable electronegativities. Improved methods of calculation have shown that the π-electron density at the 2-atom is less than unity, while at the 5- and 7-atoms the densities are more than unity, as a result of which the dipole moment is appreciably reduced.

Pseudoazulenes should possess a dipole moment greater than that of azulene. The measured dipole moment of 5-methyl-5*H*-indeno[2,1-*b*]quinoline is 2.35 D and that of 1,2;5,6-dibenzoxalene is 2.02 D. The substituents in pseudoazulenes have a striking influence, which exceeds the normal values. When electron-accepting substituents (CN, CHO, and $COOC_2H_5$) are introduced into the five-membered ring of 1,2;5,6-dibenzoxalene, the dipole moment increases much more than might have been expected on the basis of the group moments of the substituents.[103] This can be explained by the considerable contribution of the polar structure (B). This contribution is greater the more electronegative the substituent and the greater the polarisability of the pseudoazulene. The dipole moment and the polarisability of azulene in the ground state as well as in the first and second excited states have been examined.[159]

## VI. BIOLOGICAL ACTIVITY AND PRACTICAL APPLICATIONS OF PSEUDOAZULENES

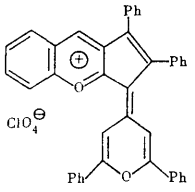
Like azulene derivatives, pseudoazulenes have a distinct biological activity. Certain alkylindolizines have a physiological activity analogous to convulsing poisons and induce the paralysis of the muscular and respiratory activity.[160]

The Mannich bases obtained from 2-phenyl and 1,2-diphenylindolizines have a depressing influence on the central nervous system.[161–166] Derivatives of indolizine-1-acetic acid have been patented as analgesic and anti-inflammatory agents.[167,168] 2-Furylindolizines exhibit an antimicrobial activity,[169] while 6-methyl-7-(2,4,5-trimethylbenzyl)-2-phenylindolizine shows growth regulating activity.[170,171] The influence of 6*H*-pyrrolo[3,2-*f*]indolizines[172–174] on the cardiovascular system, arterial pressure, and pulse has been investigated; the application of the hydrochloride of 2-ethoxycarbonyl-4-isobutyl-3,6,7,8-tetramethyl-6*H*-pyrrolo-[3,2-*f*]indolizine as an antiarrhythmic agent,[175] whose effect is several times greater than that of other antiarrhythmic agents such as quinidine and novocainamide, has been patented. Certain pseudoazulenes exhibit an antitumour activity.[176–179] The carcinogenic activity of condensed polycyclic pseudoazulenes containing the nitrogen and sulphur heteroatoms has been studied. Dibenzo[3,4,5,6]thiapyrano-[4,3-*b*]indolenine (XCIV) exhibited the maximum carcinogenic activity:[180]



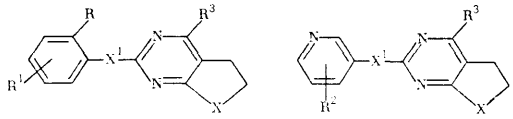
(XCIV)

It has been established that 2-arylindolizines possess no carcinogenic activity.[181] Liquid crystal derivatives of azulene have been obtained recently.[182] 2,6-Diphenyl-4*H*-4-{3*H*-1,2-diphenylbenzo[*b*]cyclopenta[*e*]-3-pyrania}pyrylium perchlorate (XCV) has been proposed as a sensitiser of photoconductivity in order to extend the range of the spectral sensitivity of electrophotographic materials to 800 nm:[183]



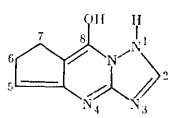
(XCV)

Sulphonamide derivatives of hydrogenated pseudoazulenes of the (XCVI) and (XCVII) types with the following substituents have been patented as herbicidal preparations:[184] R = H, Me, MeO, Hal, $NO_2$, $CF_3$, COOAlk, $SO_2Alk$, $OSO_2R$, $CF_3CH_2O_3S$, or $MeN(OMe)SO_2$; $R^1$ = H, Hal, Alk, or MeO; $R_2$ = H, Hal, Alk, AlkO, $NO_2$, COOAlk, or AlkS; $R^3$ = H, Me, MeO, Cl, or EtO; $n$ = 1 or 2; X = $(CH_2)_n$ or O; $X^1$ = NHC(Z)NH; Z = O or S.



(XCVI) (XCVII)

Polymers containing the 1,2,4-triazolo[1,3-*a*]pyrimidinyl group have been patented as stabilisers of photographic silver halide materials:[185]



The most promising trend in this field comprises studies on the biological activity and photochemical properties of compounds of the class considered.

## REFERENCES


1. H.G.Grant, P.J.O'Regan, R.J.Park, and M.D.Sutherland, Austral.J.Chem., 1980, **33**, 853.
2. C.W.Ford and M.R.Bendall, Austral.J.Chem., 1980, **33**, 509.
3. R.B.Woodward and B.Witkop, J.Amer.Chem.Soc., 1949, **71**, 379.
4. R.Bentley and T.S.Stevens, Nature, 1949, **164**, 141.
5. R.C.Elderfield, J.M.Lagowski, O.L.McCurdy, and S.L.Wythe, J.Org.Chem., 1958, **23**, 435.
6. E.E.Glover and G.Jones, J.Chem.Soc., 1958, 1750.
7. K.B.Prasad and G.A.Swan, J.Chem.Soc., 1958, 2045.
8. E.Gellert and E.R.-H.Schlittler, Helv.Chim.Acta, 1951, **34**, 642.
9. L.B.Townsend and R.K.Robins, "Nucleoside Antibiotics", Second Edition, The Chemical Rubber Co., Cleveland, Ohio, 1970.
10. R.Hall, "The Modified Nucleosides in Nucleic Acids", Columbia University Press, New York, 1971.
11. W.H.Perkin and R.Robinson, J.Chem.Soc., 1919, **115**, 933.
12. J.W.Armit and R.Robinson, J.Chem.Soc., 1922, **121**, 827.
13. J.W.Armit and R.Robinson, J.Chem.Soc., 1925, **127**, 1604.
14. G.V.Boyd, Chem.Ind., 1957, 1244.
15. R.Mayer, Angew.Chem., 1957, **69**, 481.
16. M.Los, J.P.Saxena, and W.H.Stafford, Proc.Chem. Soc., 1957, 352.
17. W.Trebs and G.Kempter, Chem.Ber., 1959, **92**, 601.
18. T.Nozoe and I.Murata, "Aromatic Compounds", London, 1973, p.201.
19. K.Hafner, "The V International Congress on the Chemistry of Heterocyclic Compounds. Abstracts of Reports", Ljubljana, 1975, p.17.
20. W.L.Mosby, "Heterocyclic Systems with Brigehead Nitrogen Atoms", Interscience, 1961, Part 1, No.4.
21. N.S.Prostakov and O.B.Baltibaev, Uspekhi Khim., 1975, **44**(9), 1649 [Russ.Chem.Rev., 1975(9)].
22. H.-J.Timpe and A.V.El'cov, Z.Chem., 1975, **15**, 172.
23. N.P.Buu-Hoi, A.Croisy, P.Jacquignon, M.Renson, and A.Ruwet, J.Chem.Soc., C, 1970, 1058.
24. H.-J.Timpe and A.V.El'cov, Z.Chem., 1975, **15**, 218.
25. R.Mayer and U.Weise, Naturwiss, 1958, **45**, 312.
26. W.Treibs and W.Schroth, Ann.Chem., 1961, **642**, 82.
27. M.Los and W.H.Stafford, J.Chem.Soc., 1959, 1680.
28. D.Leaver, J.Smolicz, and W.H.Stafford, J.Chem. Soc., 1962, 740.
29. V.N.Gogte, A.J.Namjoshi, and B.D.Tilak, Tetrahedron Lett., 1971, 4305.
30. E.Kovats, H.H.Günthardt, and P.A.Plattner, Helv.Chim.Acta, 1954, **37**, 2123.
31. K.Hafner, Angew.Chem., 1958, **70**, 419.
32. D.M.Ginsburg (Editor), "Nebenzoidnye Aromaticheskie Soedineniya" (Non-benzenoid Aromatic Compounds), Inostr.Lit., Moscow, 1963.
33. V.B.Mochalin and Yu.N.Porshnev, Uspekhi. Khim., 1977, **46**(6), 1002 (Russ.Chem.Rev.,1977(6)].
34. R.Mayer and J.Franke, J.prakt.Chem., 1964, **30**, 262.
35. F.Mayer, J.Franke, V.Horak, I.Hanker, and R.Zahradnik, Tetrahedron Lett., 1961, 289.
36. A.G.Anderson, W.F.Harrison, R.G.Anderson, and A.G.Osborn, J.Amer.Chem.Soc., 1959, **81**, 125.
37. A.G.Anderson, W.F.Harrison, and R.G.Anderson, J.Amer.Chem.Soc., 1963, **85**, 3448.
38. J.Franke and R.Mayer, J.prakt.Chem., 1963, **21**, 75.
39. H.Prinzbach and H.-J.Herr, Angew.Chem., 1972, **84**, 117.
40. K.Hafner, C.Bernhard, and R.Müller, Ann.Chem., 1961, **650**, 35.
41. K.Hafner and H.Weldes, Ann.Chem., 1957, **606**, 90.
42. W.Treibs and M.Quarg, Ann.Chem., 1956, **598**, 38.
43. L.E.Kholodav, I.F.Tishchenkova, and V.G.Iashunskii, Tetrahedron Lett., 1970, 1535.
44. I.F.Tishchenkova, L.E.Kholodov, and V.G.Yashunskii, Khim.Geterotsikl.Soed., 1971, 102.
45. J.J.Eisch and G.Gupta, Tetrahedron Lett., 1972, 3273.
46. J.J.Eisch, F.J.Gadek, and G.Gupta, J.Org.Chem., 1973, **38**, 431.
47. G.V.Boyd, J.Chem.Soc., 1958, 1978.
48. W.Treibs, W.Schroth, D.Kipping, and E.Leibnitz, Naturwiss, 1961, **48**, 430.
49. R.Mayer and H.Russ, Chem.Ber., 1962, **95**, 1311.
50. W.Treibs and W.Schroth, Angew.Chem., 1959, **71**, 71.
51. A.V.El'tsov, G.-I.Timpe, and N.I.Rtishchev, Zhur. Org.Khim., 1975, **11**, 398.
52. W.Treibs, W.Schroth, H.Lichtmann, and G.Fischer, Ann.Chem., 1961, **642**, 97.
53. H.-J.Timpe, A.V.El'cov, and N.I.Rtiscev, Chimia, 1974, **28**, 657.
54. W.Borsche and W.Menz, Ber., 1908, **41**, 190.
55. G.V.Boyd, J.Chem.Soc., 1959, 55.
56. G.N.Dorofeenko, E.I.Sadekova, and E.V.Kuznetsov, "Preparativnaya Khimiya Pirilievykh Solei" (Preparative Chemistry of Pyrylium Salts), Izd. Rostov.Univ., Rostov-on-Don, 1972, p.87.
57. G.V.Boyd and A.W.Ellis, J.Chem.Soc., B, 1966, 349.
58. G.V.Boyd and F.W.Clark, J.Chem.Soc., C, 1966, 859.
59. A.T.Balaban, W.Schroth, and G.Fischer, Adv. Heterocycl., Chem., 1969, **10**, 241.
60. A.G.Anderson and H.L.Ammon, Tetrahedron Lett., 1966, 2579.
61. A.G.Anderson and W.F.Harrison, Tetrahedron Lett., 1960, 11.
62. J.Harley-Mason and G.R.Harrison, J.Chem.Soc., 1963, 4872.
63. R.Wagner and R.Mayer, Z.Chem., 1963, **3**, 25.
64. R.Radeglia and R.Wagner, Z.Chem., 1964, **4**, 145.
65. A.G.Anderson and D.M.Forkey, J.Amer.Chem.Soc., 1969, **91**, 924.
66. W.Treibs and J.Beger, Ann.Chem., 1962, **652**, 192.
67. J.Beger and W.Treibs, Ann.Chem., 1962, **652**, 204.
68. W.Treibs and J.Beger, Ann.Chem., 1962, **652**, 212.
69. R.Dhar and W.Huehnermann, Chem.Ber., 1983, **116**, 97.
70. K.B.Prasad and G.A.Swan, J.Chem.Soc., 1958, 2045.
71. A.G.Anderson and D.M.Forkey, J.Org.Chem., 1972, **37**, 3499.
72. A.G.Anderson and W.F.Harrison, J.Amer.Chem. Soc., 1964, **86**, 708.
73. A.G.Anderson and H.L.Ammon, Tetrahedron, 1967, **23**, 3601.

74. G.Weiss and D.Schoenfeld, Tetrahedron, 1966, **22**, 2511.
75. Yu.N.Porshnev, V.A.Churkina, and N.A.Andronova, Khim.Geterotsikl.Soed., 1977, 902.
76. Yu.N.Porshnev, V.A.Churkina, and V.B.Titov, Khim.Geterotsikl.Soed., 1978, 1324.
77. A.G.Anderson and L.L.Replogle, J.Org.Chem., 1963, **28**, 2578.
78. Yu.N.Porshnev, V.I.Erikhov, M.I.Cherkashin, and V.M.Misin, Izv.Akad.Nauk SSSR, Ser.Khim., 1979, 235.
79. W.Treibs and H.Orthmann, Chem.Ber., 1960, **93**, 545.
80. W.Treibs and H.Orthmann, Naturwiss, 1958, **45**, 85.
81. R.N.McDonald and W.S.Stewart, J.Org.Chem., 1965, **30**, 270a.
82. C.Jutz, BRD P.1079629 (1960); Chem.Abs., 1961, **55**, 19883.
83. B.P.Bespalov, A.A.Pankratov, and V.V.Titov, Zhur.Org.Khim., 1974, **10**, 134.
84. K.Hafner and K.-L.Moritz, Ann.Chem., 1961, **650**, 92.
85. K.Hafner and K.-L.Moritz, Angew.Chem., 1960, **72**, 918.
86. V.A.Churkina, Candidate's Thesis in Chemical Sciences, NIOPIK, Moscow, 1978, p.80.
87. V.A.Nefedov, L.K.Tarygina, L.V.Kryuchkova, and Yu.S.Ryabokobylko, Zhur.Org.Khim., 1981, **17**, 550.
88. See Ref.86, p.76.
89. Yu.N.Porshnev, V.I.Erikhov, and M.I.Cherkashin, Khim.Geterotsikl.Soed., 1977, 1278.
90. V.I.Erikhov, Yu.N.Porshnev, and M.I.Cherkashin, Khim.Geterotsikl.Soed., 1976, 1002.
91. Yu.N.Porshnev, V.A.Churkina, and V.V.Titov, Khim.Geterotsikl.Soed., 1978, 459.
92. G.N.Dorofeenko, A.V.Koblik, T.I.Polyakova, and L.A.Murad'yan, Khim.Geterotsikl.Soed., 1980, 1045.
93. F.Kröhnke and K.Dickore, Chem.Ber., 1959, **92**, 46.
94. W.Treibs and H.Bader, Chem.Ber., 1957, **90**, 789.
95. S.F.Krivun, G.N.Dorofeenko, and A.F.Kovalevskii, Khim.Geterotsikl.Soed., 1970, 733.
96. G.I.Zhungietu, N.V.Shantsevoi, and B.P.Sukhanyuk, Zhur.Vses.Khim.Obshch.im.Mendeleeva, 1971, **16**, 232.
97. V.A.Nefedov and L.K.Tarygina, Zhur.Org.Khim., 1976, **12**, 2012.
98. B.E.Zaitsev, V.A.Churkina, G.V.Sheban, Yu.N.Porshnev, and V.V.Titov, Khim.Geterotsikl. Soed., 1978, 1329.
99. I.V.Barinov and V.A.Chertkov, Zhur.Org.Khim., 1977, **13**, 2458.
100. G.I.Timpe, E.M.Klokova, and A.V.El'tsov, Zhur. Org.Khim., 1978, **14**, 673.
101. R.Borsdorf, J.prakt.Chem., 1966, **32**, 216.
102. R.Borsdorf, Z.Chem., 1964, **4**, 422.
103. R.Borsdorf, W.Schroth, and G.Fischer, Z.Chem., 1964, **4**, 68.
104. R.Borsdorf, Z.Chem., 1965, **5**, 187.
105. R.Borsdorf, Z.Chem., 1963, **3**, 119.
106. R.Zahradnik and C.Prakanui, Coll.Czech.Chem. Comm., 1965, **30**, 3016.
107. J.Fabian, A.Mehlhorn, and R.Zahradnik, J.Phys. Chem., 1968, **72**, 3975.
108. R.Zahradnik and J.Kontecky, Tetrahedron Lett., 1961, 632.
109. R.Zahradnik and J.Kotecky, Coll.Czech.Chem. Comm., 1963, **28**, 1117.
110. E.M.Elveth, Theor.Chim.Acta, 1970, **16**, 22.
111. J.Fabian, A.Mehlhorn, and R.Zahradnik, Theor. Chim.Acta, 1968, **12**, 247.
112. Yu.B.Vysotskii and B.P.Zemskii, Khim.Geterotsikl. Soed., 1980, 984.
113. A.Streitwieser, "Molecular Orbital Theory for Organic Chemists" (Russian translation edited by M.E.Dyatkina), Izd.Mir, Moscow, 1965, p.429.
114. A.Julg, Compt.rend.C, 1954, **239**, 1498.
115. P.A.Plattner, A.Fürst, and K.Zirasek, Helv.Chim. Acta, 1947, **30**, 1320.
116. W.Treibs, Naturwiss, 1962, **49**, 37.
117. P.A.Plattner, A.Fürst, Z.Chopin, and G.Winteler, Helv.Chim.Acta, 1948, **31**, 501.
118. P.A.Plattner, A.Fürst, and W.Keller-Schierlein, Helv.Chim.Acta, 1949, **32**, 2464.
119. E.Kloster-Jensen, E.Kovats, A.Eschenmoser, and E.Heilbronner, Helv.Chim.Acta, 1956, **39**, 1051.
120. K.Zeigler and K.Hafner, BRD P.2766304 (1956); Chem.Abs., 1957, **51**, 12981.
121. C.Jutz and E.Schweiger, Chem.Ber., 1974, **107**, 2383.
122. E.A.Braude and W.F.Forbes, J.Chem.Soc., 1953, 2208.
123. W.Treibs, Ann.Chem., 1952, **577**, 201.
124. A.M.Islam and R.A.Raphael, J.Chem.Soc., 1953, 2247.
125. T.Watanabe and N.Soma, Chem.Pharm.Bull., 1971, **19**, 2215.
126. K.Hafner and H.Weldes, Ann.Chem., 1958, **618**, 145.
127. K.Hafner, J.Märing, and W.Jakel, Angew.Chem.Int. Ed., 1970, **9**, 159.
128. P.A.Plattner, A.Fürst, M.Gordon, and K.Zimmerman, Helv.Chim.Acta, 1950, **33**, 1910.
129. N.J.Turro, "Molecular Photochemistry" (Translated into Russian), Izd.Mir, Moscow, 1967, 57.
130. J.B.Berlmann, "Handbook of Fluorescence Spectra of Aromatic Molecules", Acad.Press., 1971, No.7, p.94.
131. A.E.W.Kinght and B.K.Selinger, Chem.Phys.Letters, 1971, **12**, 419.
132. R.H.Huebrer, W.F.Frey, and R.N.Compton, Chem. Phys.Letters, 1971, **23**, 587.
133. A.Olszonski, J.Lipinski, and H.-J.Timpe, J.Mol. Struct., 1979, **53**, 251.
134. K.Hafner, H.Patzelt, and H.Kaiser, Ann.Chem., 1962, **656**, 24.
135. A.G.Anderson, J.Org.Chem., 1972, **37**, 3499.
136. Yu.N.Porshnev, N.A.Andronova, E.M.Tereshchenko, and K.Z.Ogorodnik, Zhur.Org.Khim., 1974, **10**, 2602.
137. B.E.Zaitsev, V.A.Churkina, and Yu.N.Porshnev, Khim.Geterotsikl.Soed., 1980, 1030.
138. G.Levy and G.Nelson, "Manual of Carbon-13 Nuclear Magnetic Resonance for Organic Chemists" (Translated into Russian), Izd.Mir, Moscow, 1975.
139. A.J.Jones, P.D.Gardner, D.M.Grant, W.M.Lichtman, and V.Boekelheide, J.Amer.Chem.Soc., 1970, **92**, 2395.
140. S.Braun and J.Kinkejder, Tetrahedron, 1977, **33**, 1827.
141. W.G.Schneider, H.J.Mernstein, and J.A.Pople, J.Amer.Chem.Soc., 1958, **80**, 3497.
142. B.I.Ionin and B.A.Ershov, "YaMR-Spektroskopiya v Organicheskoi Khimii" (NMR Spectroscopy in Organic Chemistry), Izd.Khimiya, Leningrad, 1967, p.245.
143. A.G.Anastassion and S.J.G.Reichmanis, J.Amer. Chem.Soc., 1977, **99**, 7392.

144. V.A.Nefedov and L.K.Tarygina, Zhur.Org.Khim., 1976, **12**, 1763.
145. Yu.N.Porshnev, V.I.Erikhov, and M.I.Cherkashin, Dokl.Akad.Nauk SSSR, 1979, **248**, 118.
146. Yu.N.Porshnev, V.I.Erikhov, and M.I.Cherkashin, Zhur.Org.Khim., 1976, **12**, 2599.
147. Yu.N.Porshnev, V.I.Erikhov, and N.A.Andronova, Zhur.Org.Khim., 1977, **13**, 2405.
148. Yu.N.Porshnev, V.I.Erikhov, and M.I.Cherkashin, Izv.Akad.Nauk SSSR, Ser.Khim., 1976, 1643.
149. Yu.N.Porshnev, V.I.Erikhov, N.A.Andronova, V.M.Misin, and M.I.Cherkashin, Dokl.Akad.Nauk SSSR, 1981, 256, 881.
150. T.S.Loseva, M.S.Goizman, L.M.Alekseeva, O.R.Shvarts, E.E.Mikhlina, and L.N.Yakhontov, Khim.Geterotsikl.Soed., 1978, 802.
151. L.M.Alekseeva, G.G.Dvoryantseva, M.S.Goizman, T.S.Loseva, A.D.Anina, E.E.Mikhlina, Yu.N.Sheinker, and L.N.Yakhontov, Khim.Geterotsikl.Soed., 1976, 1540.
152. T.S.Loseva, A.D.Yanina, E.E.Mikhlina, and L.N.Yakhontov, Khim.Geterotsikl.Soed., 1976, 209.
153. T.S.Loseva, A.D.Yanina, E.E.Mikhlina, and L.N.Yakhontov, Khim.Geterotsikl.Soed., 1976, 348.
154. N.P.Buu-Hoi, A.Croisy, P.Jacquignon, A.Martani, and R.Ricci, J.Heterocycl.Chem., 1970, **7**, 931.
155. J.Deutsch, L.Neiman, and F.Bergmann, Org.Mass Spectrom., 1971, **5**, 279.
156. A.G.Anderson and B.M.Steckler, J.Amer.Chem.Soc., 1959, **81**, 4941.
157. P.Pariser, J.Chem.Phys., 1956, **25**, 1112.
158. R.D.Brown and M.L.Hefferman, Austral.J.Chem., 1960, **13**, 38.
159. W.Baumann, Chem.Phys., 1977, **20**, 17.
160. T.Hirosawa, Proc.Japan Pharmacol.Soc., 1938, **12**, 218.
161. W.B.Harrell, J.Pharm.Sci., 1970, **59**, 275.
162. W.B.Harrell and R.F.Doerge, J.Pharm.Sci., 1968, **57**, 1989.
163. W.B.Harrell, S.M.Kuang, and C.O.Dell, J.Pharm. Sci., 1970, **59**, 721.
164. L.A.Walter and P.Margolis, J.Med.Chem., 1968, **10**, 498.
165. W.B.Harrell and R.F.Doerge, J.Pharm.Sci., 1967, **56**, 225.
166. W.B.Harrell and R.F.Doerge, J.Pharm.Sci., 1967, **56**, 1200.
167. A.G.Brown and J.H.C.Nayler, BRD P.2 046 904 (1971); Chem.Abs., 1971, **75**, 48933.
168. C.Casagrande, A.Inverizzi, R.Ferrini, and G.Miragoli, Farmaco (Ital.), 1971, **26**, 1059.
169. N.O.Saldabol et al., Khim.-Farm.Zhur., 1970(4), 20.
170. N.S.Prostakov, A.T.Soldatenkov, V.O.Fedorov, S.Mobio, and M.A.Galiullin, Khim.Geterotsikl. Soed., 1980, 1511.
171. N.S.Prostakov, P.K.Radzhan, and A.T.Soldatenkov, Khim.Geterotsikl.Soed., 1980, 1516.
172. A.F.Mironov et al., Zhur.Org.Khim., 1977, **13**, 1306.
173. A.F.Mironov et al., Khim.Geterotsikl.Soed., 1977, 777.
174. A.F.Mironov et al., Dokl.Akad.Nauk SSSR, 1978, **241**, 1093.
175. V.V.Zakusov et al., USSR P.606 582 (1978); Byul.Izobret., 1978(17).
176. T.E.Young and P.H.Scott, US P.3 388 133 (1968); Chem.Abs., 1968, **69**, 59213.
177. T.E.Young and P.H.Scott, US P.3 388 134 (1968); Chem.Abs., 1968, **69**, 67357.
178. A.Lacassage et al., Europ.J.Cancer, 1968, **4**, 219.
179. N.P.Buu-Hoi, P.Jacquignon, A.Croisy, and A.Ricci, J.Chem.Soc.(C), 1968, 45.
180. F.Zajdela, N.P.Buu-Hoi, P.Jacquignon, A.Croisy, and F.Perin, J.Nat.Cancer Inst., 1971, **46**, 1257.
181. N.P.Buu-Hoi, L.C.Binh, T.B.Loc, N.D.Xuong, and P.Jacquignon, J.Chem.Soc., 1957, 3126.
182. K.Praefcke and D.Schmidt, Z.Naturforsch., 1981, 36b, 375.
183. E.I.Balabanov, et al., USSR P.756 344 (1980); Byul.Izobret., 1980(30).
184. G.Levitt, US P.4 339 267 (1982); Chem.Abs., 1983, **98**, 215602.
185. Ishiguro Shofi, et al., BRD P.3 223 316 (1983); Chem.Abs., 1983, **98**, 225245.

Institute of Chemical Physics,
USSR Academy of Sciences,
Moscow