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The Problem of Tetrahedrane

N.S.Zefirov, A.S.Koz'min, and A.V.Abramenkov

The theoretical and experimental studies on tetrahedrane—a highly strained compound—are surveyed. The bibliography includes 87 references.

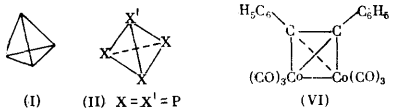
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I. INTRODUCTION

After Baeyer proposed his "strain" theory based on simple geometrical considerations, organic chemists devoted much experimental labour, perseverance, and intellectual effort to the synthesis of highly strained structures. Purely geometrical approaches frequently serve as a starting point in the synthesis of skeletal and polycyclic compounds. It is sufficient to point out as an example the synthetic research in the field of tri- and penta-prismanes and related structures[1-5], propellanes[6], cubane[7-9], homotetrahedrane[10,11], dodecahedrane[12-14], etc., let alone the thoroughly developed field of the chemistry of adamantane[15], its heterologues[16], and higher derivatives ("adamantalogues")[17,18]. The fact that polyhedranes with a high symmetry are aesthetically attractive is itself a sufficient stimulus for "molecular design"[19]. However, the continued attention devoted by chemists to skeletal and polyhedral structures is naturally not due solely to abstract interest; these compounds frequently possess surprising properties, which makes their synthesis of interest from both theoretical and practical points of view. In particular, the chemistry of adamantane provides numerous examples of this. We may note here the problem of "molecular strain"[20], the dependence of the bond properties on the distortion of valence angles (for example, $J_{^{13}C-H}$ and the change in hybridisation), the stereochemistry of the inductive effect[22-24], etc., which have been examined using skeletal and polyhedral structures as models.

Organic molecules belonging to the T_d symmetry point group, the simplest of which is tetrahedrane (I), are of special interest in this respect.



(I) (II) X = X' = P
(III) X = X' = BCl
(IV) X' = CH_3C, X = $B(C_2H_5)_3$
(V) X' = RC, X = $Co(CO)_3$
(VI)

From the topological point of view, this molecule is interesting because its hydrocarbon skeleton constitutes the simplest connected cubic graph[25]. The very marked distortion of all the valence angles in the molecule should lead to enormous strain, which apparently reaches its limiting value for an organic molecule. We may also formulate several problems which make the task of synthesising tetrahedrane structures exceptionally urgent. The enormous strain in the tetrahedrane molecule should lead to a unique reactivity of the σ-bonds. Examples of a sharp change in the electronic structure of a formally single bond owing to strain, as, for example, in certain propellanes[6] and dehydroadamantane[26], are known in the literature. This property should be particularly striking in the tetrahedrane molecule. Another problem is associated with the study of the optical activity of structures having tetrahedral symmetry but no chiral centre. This problem has also been considered in relation to adamantane derivatives[27-29]. Finally heterotetrahedranes, in which new specific problems arise, such as that of the basicity of the heteroatom (nitrogen, phosphorus), complex formation, etc., might also be of considerable interest.

We may note that non-carbon tetrahedral structures, which may be assigned at least formally to heterotetrahedranes, have now been described. The simplest heterotetrahedrane is the P_4 molecule (II).[30] Tetrahedral structures are known for boron derivatives, for example (III)[31] and (IV)[32]. The cobalt clusters (V)[33] or (VI)[34] have the molecular topological form of tetrahedrane†.

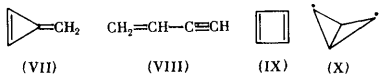
However, the synthesis of the tetrahedrane carbon skeleton is of greatest interest. There is as yet no clear-cut description of the synthesis of tetrahedrane and only indirect evidence is available for the existence of molecules of this type. Nevertheless the literature devoted to this problem is fairly extensive and, bearing in mind the enormous fundamental importance of the problem, we thought it is useful to survey it, noting both theoretical and experimental advances.

II. THEORETICAL STUDY OF TETRAHEDRANE

As stated above, tetrahedrane is the most strained system among all possible saturated compounds containing

† This concept was introduced by one of the present authors (N.S.Zefirov) and by V.N.Drozd, V.I.Sokolov, and I.V.Stankevich. By the term molecular topological form, we understand the figure in the usual sense of the word plus certain singular points (atoms within the figure, the centre of inversion). For example, the molecular topological form for tetrasubstituted methane is a tetrahedron with a single singular point, while for hexasubstituted ethane it is an octahedron with two singular points. This concept serves as a basis for the definition of the most important stereochemical concept—that of configuration (configuration is the stereochemical equivalent of the topological form of the molecule). For the tetrahedron molecules considered in this study, the molecular topological form is a tetrahedron without internal points.

three-membered rings. The angular geometrical parameters of this molecule are fully determined by its symmetry and only the C–C and C–H distances can vary independently. Comparison of the geometry of tetrahedrane with that of bicyclo[1,1,0]butane shows that the dihedral angle between the three-membered rings in the latter is close to 126°, whilst in the tetrahedrane the corresponding angle should be 70°32′.[35] In this connection the problem arises of the thermodynamic stability of tetrahedrane in relation to the family of the isomeric C_4H_4 structure. Among these, we may note structures with closed shells such as those of methylenecyclopropene (VII), vinylacetylene (VIII), and cyclobutadiene (IX)‡. However, the main factor which determines the possibility of the existence of an isolated tetrahedrane molecule is the form of the potential energy hypersurface for the C_4H_4 system (in particular the presence of a minimum at the point corresponding to the tetrahedral configuration and the size of the potential barriers separating tetrahedrane from its possible conversion products).



(VII) (VIII) (IX) (X)

Apart from the structures enumerated above, the system comprising two acetylene molecules and the biradical (X), obtained from tetrahedrane following the dissociation of a single C–C bond, may be assigned to systems of this kind. Regardless of thermodynamic stability, in the presence of large potential barriers the tetrahedrane molecule might exist as a long-lived metastable species. The most important theoretical study of the present problem is therefore that of the potential energy of the C_4H_4 system as a function of the geometrical configuration of the nuclear skeleton.

1. Investigation of the Potential Energy Surface for the C_4H_4 System

Since the geometry of the C_4H_4 system is determined by eighteen independent variables (geometrical parameters), the potential energy can be represented by a hypersurface in a 19-dimensional space. A quantum-mechanical calculation even for a small section of such a hypersurface is impossible in the present state of computing technique. By virtue of these factors, theoretical estimates of the energies of individual isomers with specified geometries are easiest at the present time. Calculations of the total energies of various isomers having the formula C_4H_4 and their estimation from thermodynamic characteristics have been made within the framework of semiempirical molecular orbital methods[36,38-40]; non-empirical quantum-mechanical calculations have become possible recently[37,41-43].

The relative distribution of the C_4H_4 isomers in terms of energies, based on the results of a non-empirical calculation by the Hartree–Fock method[43], is illustrated in Fig. 1. One should bear in mind that in this approximation the energies obtained for certain systems are much too high. This applies particularly to cyclobutadiene (IX) and one must therefore expect that the difference between the energies of tetrahedrane and cyclobutadiene is much greater than 30–50 kcal mole^{-1}. An adequate description of the above system becomes possible when configurations with open shells are introduced into the wave function. In the calculations taking into account the configuration interaction the energy of the ground state of tetrahedrane is found to be higher by 70.3 kcal mole^{-1} than that of cyclobutadiene[41]. Similar values (73–84 kcal mole^{-1}) are given by the semi-empirical PPP, PNDO, and MINDO methods[36,38,39]. Comparison of the energies of cyclobutadiene and two acetylene molecules leads to highly conflicting results, depending on the method of calculation. Thus, according to semi-empirical calculations, the energy of the cyclobutadiene molecule is lower than that of the pair of acetylene molecules by an amount ranging from 2 to 50 kcal mole^{-1}.[36,44] However, the results of a non-empirical calculation by the method of configuration interaction, according to which the pair of acetylene molecules has a lower energy than that of the cyclobutadiene molecule, are more reliable, the difference being estimated as 0–30 kcal mole^{-1}.[37,41] If one takes into account the lower limit of the semi-empirical estimate, then, presumably, cyclobutadiene and a pair of acetylene molecules constitute virtually isoenergetic systems.

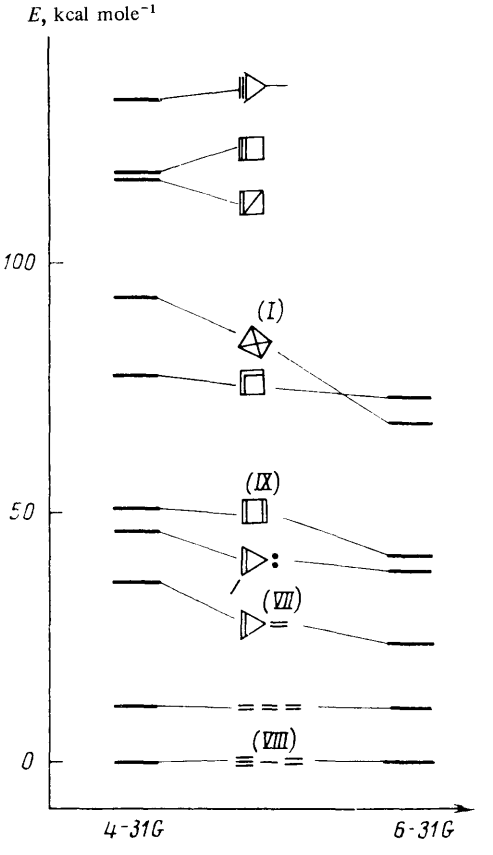


Figure 1. The relative energies of a number of C_4H_4 isomers (relative to but-3-en-1-yne) calculated in terms of the one-determinant approximation of the MO SCF method using 4-31 G and 6-31 G extended Gaussian basis sets[43].

‡ The simple Hückel molecular orbital method leads to a triplet configuration for the ground state of cyclobutadiene. For further details, see Dewar and Gleicher[36] and Buenker and Peyerimhoff[37].

When the possible pathways towards the isomerisation of tetrahedrane are considered, direct conversion into cyclobutadiene or decomposition into two acetylene molecules are thought to be unlikely, since these processes are forbidden by the principle of the conservation of orbital symmetry[42]. The most probable initial stage in the isomerisation is the dissociation of one of the C–C bonds with formation of the bicyclobutyl biradical (X). According to the results of a non-empirical calculation, the planar biradical should have an energy higher by 30–50 kcal mole^{-1} than that of tetrahedrane and higher by 100–120 kcal mole^{-1} than that of cyclobutadiene[41]. Estimation of the energy of the non-planar biradical with the geometry of bicyclobutane itself by semi-empirical methods leads to higher values than the energy of tetrahedrane by an amount ranging from 2 to 11 kcal mole^{-1}.[39] The equilibrium geometry of the biradical was not determined, since the above estimates are only approximate. Nevertheless they permit the assumption that tetrahedrane and the bicyclobutyl biradical have similar energies, that of the biradical being lower. The most probable schematic distribution of energy levels corresponding to tetrahedrane, cyclobutadiene, the biradical (X), and a pair of acetylene molecules, constructed on the basis of the above calculations, is presented in Fig. 2.

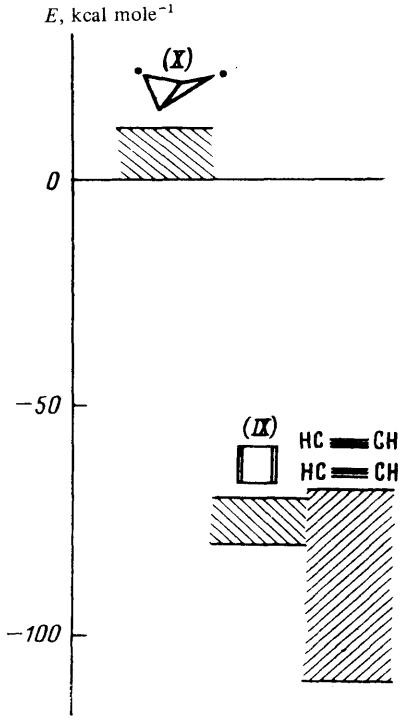


Figure 2. The probable energy ranges of the possible tetrahedrane conversion products (the tetrahedrane energy was adopted as the zero level).

The enthalpies of formation of tetrahedrane at 0 K, estimated from the total energies calculated by different methods, agree to within 15 kcal mole^{-1}; the following values have been obtained: 146.1 kcal mole^{-1} (PNDO method[38]), 135.2 kcal mole^{-1} (MINDO method[39,40]), and 129–137 kcal mole^{-1} (non-empirical calculation by the MO SCF method in terms of an extended Gaussian basis set[42]). The strain energy in tetrahedrane is estimated as 142.8 kcal mole^{-1} with a deviation from additivity (i.e. from the sum of the strain energies of the four three-membered rings) of 18.0 kcal mole^{-1}.[40] The first ionisation potential of tetrahedrane (the removal of an electron from the $1e$ orbital), calculated in terms of the PNDO approximation, is 9.58 eV,[38] in good agreement with the non-empirical calculation, which gives 10.35 eV.[41] For comparison, we may indicate the ionisation potentials of certain hydrocarbons[45]: 12.71 eV for methane, 11.50 eV for ethane, 11.07 eV for propane, 10.63 eV for n-butane, 10.6 eV for cyclobutane, 10.06 eV for cyclopropane, 9.45 eV for spiropentane, and 8.74 eV for cubane.

As already mentioned, the construction of the complete potential energy hypersurface for the C_4H_4 system is too difficult. However, in the region of the equilibrium geometry of tetrahedrane the calculation of the potential energy surface becomes possible in view of the high symmetry of the molecule. The number of types of normal vibrations is 8, and the potential energy matrix contains only 13 independent elements (without taking into account the symmetry, the number of the independent matrix elements would have been 171). Calculation performed by the non-empirical MO SCF method yields positive force constants for all the normal vibrations[42], which means that a local minimum on the C_4H_4 potential energy surface corresponds to tetrahedrane. The equilibrium geometrical parameters are $R_{C-H} = 1.054$ Å and $R_{C-C} = 1.482$ Å, the accuracy of the determination of which is estimated as to within 0.01 Å. The force constants for the extension of the C–H and C–C bonds proved to be 6.5 and 4.6 mdyn Å^{-1} respectively. Comparison with other hydrocarbons permits the conclusion that the C–H bond in tetrahedrane is similar to the analogous bond in acetylene, while the C–C bond is close to the ordinary single bond.

Sections through the potential energy surfaces of the excited electronic states of tetrahedrane, corresponding to the extension of the C–C bonds with a fixed C–H distance and retention of tetrahedral symmetry, have also been obtained[41]. It was found that none of the excited states is bound in relation to such deformation, at least for C–C distances ranging from 1.38 to 1.69 Å.

The possibility of the prolonged existence of an isolated tetrahedrane molecule can be inferred from the estimate of the barrier to the transformation into the bicyclobutyl biradical (X).[42] It has been suggested that motion along the reaction coordinate along the initial section corresponds to an increase in the length of one of the C–C bonds with a simultaneous change of the C–C–H angles. With increase of the distance between the nuclei of the C–C bond ruptured in this transformation to 1.812 Å (which corresponds to an increase in the dihedral angle between the three-membered rings of approximately 20°) and following the optimisation of the C–C–H angles, the energy increases by 18 kcal mole^{-1} compared with that of the equilibrium tetrahedral configuration. This value is adopted as the lower limit of the potential barrier. Calculation for the first excited triplet state of the deformed tetrahedrane molecule yields 45 kcal mole^{-1} as the vertical excitation energy, whence it follows that the excited state does not influence the initial stage of the isomerisation process.

2. The Electronic Structure of the Tetrahedrane Molecule

In order to elucidate the nature of the chemical bonds in the tetrahedrane molecule, it is of interest to calculate the distribution of electron density and to analyse the wave functions. The distribution of the valence electron density has been calculated[46] by the extended Hückel method. In each of the three-membered tetrahedrane rings, the electron density is distributed in the same way as in the cyclopropane molecule. In particular, there are two electron density maxima on the outer side of each of the edges of the tetrahedron formed by the straight lines joining the C nuclei. At the centre of the tetrahedron and in the centre of each face, the electron density has a minimum. Overall, the pattern obtained shows that the nature of the C–C bond in tetrahedrane is close to that of a single bond in saturated hydrocarbons and differs significantly from the acetylenic bond.

Much attention has been devoted to the study of the hybridisation in tetrahedrane[42,47-49]. According to the results of various calculations, the localised hybrid molecular orbitals corresponding to the C–C bonds have 79–83% of *p* character and deviate from the direction of the bond by 30–39°. The hybrid molecular orbitals of the C–H bonds have 45–62% of *p* character. For comparison, we may note that the fractions of *p* character in the molecular orbitals of the C–C and C–H bonds of cubane are 80 and 61% respectively and that the distortion of the hybrid molecular orbital in the direction of the C–C bond is by approximately 11°. In cyclopropane the molecular orbitals of the C–C bonds have 81% of *p* character. Thus the amount of *p* character in the hybrid molecular orbitals of the C–C bonds in tetrahedrane is greater than in other saturated systems with small rings, which confirms the intuitive idea that the tetrahedrane structure involves maximum strain.

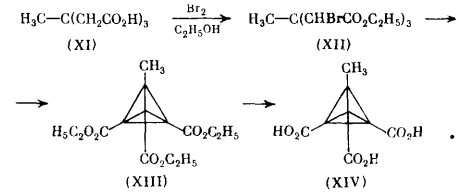
The correlation between the hybridisation parameters and the NMR constants has been used[42] to estimate the constants for the spin–spin interaction of the nuclei. The value $J_{^{13}C-H} = 240$ Hz obtained for tetrahedrane is intermediate between the values of $J_{^{13}C-H}$ for cyclopropene (220 Hz) and acetylene (251 Hz). The value $J_{^{13}C-^{13}C} = 7.1$ Hz for tetrahedrane is smaller than for cyclopropane (10 Hz) and bicyclobutane (21 Hz).

In conclusion, we may mention the theoretical prediction of the reactivity of tetrahedrane. The results of a study of the interaction of the valence electrons with an external charge within the framework of the electrostatic model based on the Hellmann–Feynman theorem have been used to examine the protonation reaction[50]. The equilibrium constant obtained shows that the tetrahedrane molecule should be protonated at pH $\leq$ 16.2. Despite its extremely approximate nature, this estimate indicates a high reactivity of tetrahedrane.

Summarising the theoretical studies, we may conclude that tetrahedrane corresponds to a metastable state of the C_4H_4 system and that the lifetime of an isolated molecule in the ground state may be fairly long. Electronic excitation should lead to the decomposition of the tetrahedrane molecule. Its high tendency towards protonation apparently necessitates the complete exclusion of all compounds containing mobile hydrogen atoms in attempts at synthesis.

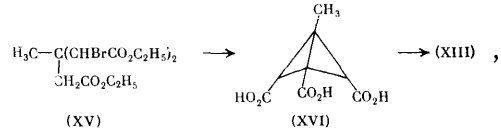
III. EXPERIMENTAL APPROACHES TO THE SYNTHESIS OF TETRAHEDRANE

Beesly and Thorpe[51] were the first to propose a method for the synthesis of a compound having the tetrahedrane structure and must be regarded as the pioneers in the research on the synthesis of tetrahedrane. They found that the tricarboxylic acid (XIV) can be obtained from ββ-dimethylpropanetricarboxylic acid (XI) via the corresponding tribromoester (XII), which is converted into the tetrahedrane derivative (XIII) in 12% yield on treatment with aqueous alkali:



(XI) (XII) (XIII) (XIV)

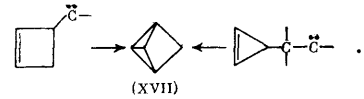
They also quote the experimental conditions for the synthesis of compound (XIII) from the tricarboxylic acid (XIV) formed on cyclisation of the dibromotriester (XV). The synthetic scheme and the absence of olefinic bonds according to the results obtained for the reaction of the product with bromine and potassium permanganate,



(XV) (XVI)

are believed to constitute proof of the proposed structure (XIII). In a separate article in the same volume of the Journal of the Chemical Society[52] Ingold carried out a simple calculation of the Baeyer strain and concluded that the existence of structures of this kind is possible.

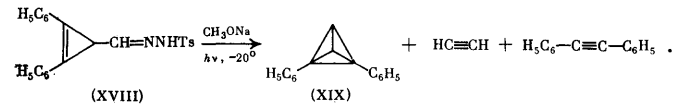
For a long time chemists found the results of the above studies[51] surprising but reliable[53]. Furthermore, the ester formed by the acid (XIV) and cellulose was recommended for industrial manufacture[54] because of certain "useful" properties. However, almost forty years later Larson and Woodward[55] failed in their attempt to reproduce the synthesis of the acid (XVI) from compound (XV). When the latter was treated with an aqueous solution of alkali, the main reaction products were acetic acid and the initial acid (XI); no cyclic compounds could be isolated from the reaction mixture. The study by Larson and Woodward stimulated the development of research on the synthesis of highly strained compounds. The structure of tricyclo[1,1,1,$0^{2,5}$]pentane (XVII) was closest to that of tetrahedrane. It was obtained by two different methods in accordance with the following schemes[10,11,56]:



(XVII)

It is not fortuitous that compounds capable of generating in different ways a carbene centre linked to a cyclopropene ring have been proposed as precursors for the specific synthesis of tetrahedrane. Masamune and Kato[57] reported in 1965 the photochemical decomposition of the sodium salt of the tosylhydrazone of Δ^2-2,3-diphenylcyclopropenealdehyde (XVIII) into diphenyltetrahedrane with a yield of 0.1%. The structure of the product, having the overall formula $C_{16}H_{12}$ and a melting point of 133.5°C, was confirmed by infrared, ultraviolet, and ^{1}H NMR spectroscopic data. However a year later, the authors[58] proposed structures (XX) or (XXI) for the product of the above reaction, i.e. the structures of isomeric hydrocarbons which should have the same physicochemical characteristics as those proposed previously for the tetrahedrane

derivative (XIX).

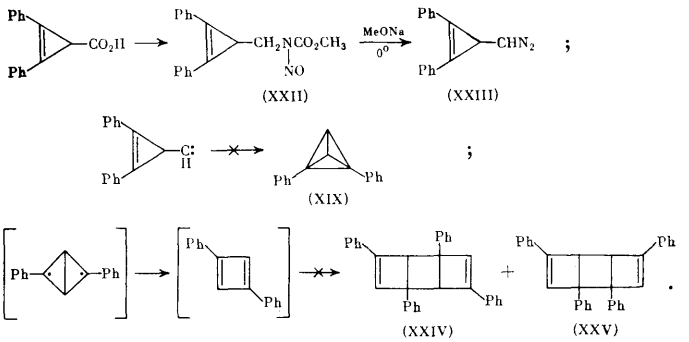


(XVIII) (XIX)



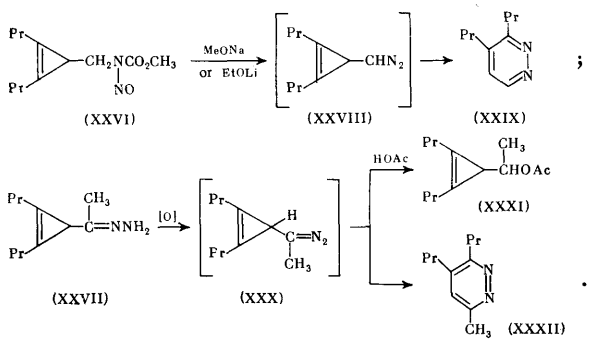
(XX) (XXI)

The prospect of using a substituted cyclopropenylcarbene attracted many investigators. For this reason, other reactions were used to generate this intermediate species and in all cases much attention was devoted to proving the formation of the carbene precursor—the corresponding diazo-compound. For example, Δ^2-2,3-diphenylcyclopropenyldiazomethane (XXIII), obtained[59] by treating with sodium methoxide the corresponding *N*-nitrosourethane (XXII), synthesised in six stages from 1,2-diphenylcyclopropenecarboxylic acid, was identified by its infrared spectrum. The diazoalkane (XXIII) proved to be extremely unstable in relation to the action of water and protic compounds. Its photolysis and thermolysis yielded neither tetrahedrane derivatives nor dimeric products based on cyclobutadiene.



(XXII) (XXIII) (XIX) (XXIV) (XXV)

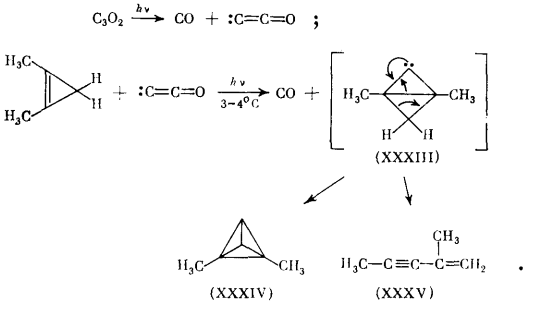
The only product that could be identified was diphenylacetylene. The conditions for the synthesis and the reactivities of diazo-compounds of the cyclopropene series were carefully investigated somewhat later[60]. Two methods were used to synthesise them: the decomposition of the *N*-nitrosourethane (XXVI) and oxidation of the hydrazone (XXVII). The decomposition of the *N*-nitrosourethane by various bases and in different solvents led in all cases to a mixture of substances, among which only 3,4-dipropylpyridazine (XXIX) could be regarded as a product formed as a result of the 1,4-sigmatropic rearrangement of dipropylcyclopropenyldiazomethane (XXVIII).



(XXVI) (XXVIII) (XXIX) (XXVII) (XXX) (XXXI) (XXXII)

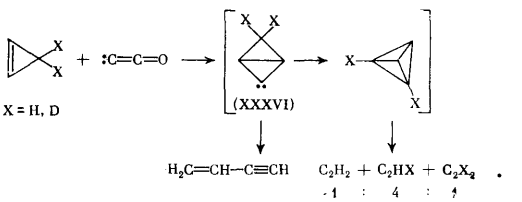
Analysis of the reaction mixture obtained in the oxidation of the hydrazone (XXVII) by lead tetra-acetate or mercury(II) oxide also led to the conclusion that the corresponding diazo-compound is formed as an intermediate. Since the subsequent transformations of the diazo-alkane (XXX) into the corresponding pyridazine are slow, oxidation with lead tetra-acetate initially involves a faster decomposition of this unstable compound into the acetate (XXXI), while oxidation with mercury(II) acetate leads to the formation of the pyridazine (XXXII). The authors[60] do not quote data concerning the behaviour of the diazo-compounds on heating or irradiation but note that but-1-yne was not detected in any of the reactions.

Another pathway, in which cyclopropene was also used as the initial compound, presupposed the intermolecular addition of the carbene generated from carbon suboxide. This method consisted in the photolysis of the latter in solution in 1,2-dimethylcyclopropene[61]. It was postulated that the carbene generated from C_3O_2 following the elimination of carbon monoxide may add to the olefinic bond of cyclopropene with formation of the intermediate bicyclic carbene (XXXIII), which may be stabilised by conversion into the tetrahedrane (XXXIV) as a result of intramolecular insertion into one of the C–H bonds.



(XXXIII) (XXXIV) (XXXV)

However, after irradiating the reaction mixture, it was possible to isolate only 2-methylpent-1-en-3-yne (XXXV) as the main photolysis product and pent-2-yne, which was formed as a result of the rearrangement of the initial 1,2-dimethylcyclopropene. The strain in the carbene (XXXIII) is apparently fairly high, so that its rearrangement to the acyclic hydrocarbon (XXXV) is faster than the intramolecular insertion with formation of the strained tetrahedrane ring. In a subsequent report Shelvin and Wolf[62] showed that, when a mixture of carbon suboxide and cyclopropene is irradiated, acetylene, which may be a product of the decomposition of the intermediate tetrahedrane, is formed in addition to vinylacetylene. The fact that acetylene is formed from tetrahedrane was confirmed using cyclopropene labelled with deuterium in the 3-position. Mass-spectrometric analysis of the acetylene fraction established that the compounds C_2H_2, C_2HD, and C_2D_2 are present in the reaction mixture in proportions of 1 : 4 : 1, which indicates the distribution of deuterium atoms at different carbon atoms of the tetrahedrane molecule, formed as a result of intramolecular insertion in the bicyclic carbene (XXXVI):



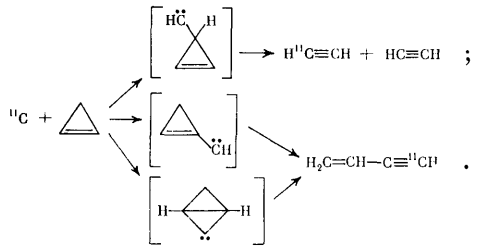
X = H, D (XXXVI)

$H_2C{=}CH{-}C{\equiv}CH$ $C_2H_2 + C_2HX + C_2X_2$

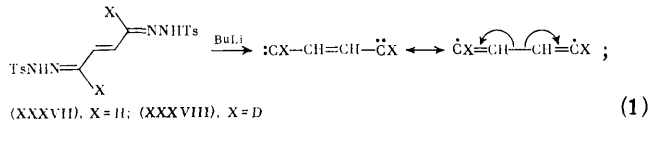
1 : 4 : 1

Additional data confirming the intermediate formation of tetrahedrane were obtained using carbon suboxide in which the central atom was labelled with ^{14}C. The authors[62] note that cyclobutadiene cannot be an intermediate in this reaction, because insertion of the ketocarbene in the C–D or the vinyl C–H bond should predominate in this case. However, it has been shown earlier that $:C_2O$ usually adds more readily to the multiple bond. Furthermore, the decomposition of cyclobutadiene into two acetylene molecules is also uncharacteristic[63].

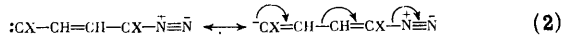
Atomic carbon generated in a nuclear reactor and triplet carbonylcarbene generated by the photolysis of carbon suboxide have also been used as the carbene capable of adding to cyclopropene. Quantitative analysis of the composition of the reaction products led to the hypothesis of the intermediate formation of tetrahedrane in this case too:



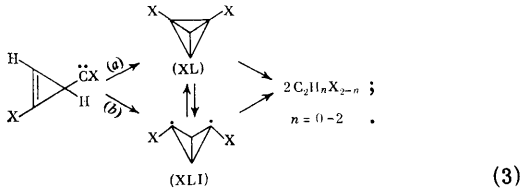
One of the possible approaches to the synthesis of tetrahedrane, which also included carbenes as intermediates, was proposed in 1973 by Rodewald and Lee[65]. They chose the bistosylhydrazone of *trans*-butenedial (XXXVII) as the source of the dicarbene. The decomposition products of the lithium salt of compound (XXXVII) at 140°C in tetrahydrofuran were collected at −80° and −190°C and investigated by preparative gas–liquid chromatography (GLC). Vinylacetylene, benzene, cyclo-octatetraene, and *syn*-$\Delta^{3,7}$-tricyclo[4,2,0,$0^{2,5}$]octadiene, which might have been formed from cyclobutadiene, were absent from the condensates. The only decomposition product was acetylene (unidentified polymers were also present). Having used the deuterium-labelled bistosylhydrazone (XXXVIII) as the starting material and having determined the distribution of the label by analysing the resulting acetylenes for deuterium, the authors proposed[65] the following mechanism for the formation of acetylenes with participation of tetrahedrane as one of the intermediates:



(XXXVII), X = H; (XXXVIII), X = D (1)



(2)

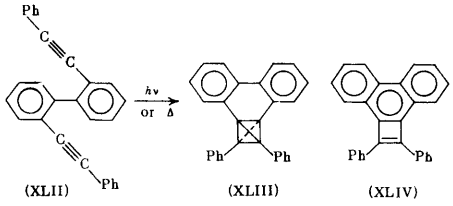


(XLI) (3)

Only C_2HD may be formed in reactions (1) and (2). The proportions of C_2H_2, C_2HD, and C_2D_2 should be 1 : 4 : 1 for pathway (*a*) and 1 : 6 : 1 for pathway (*b*) (if the process is irreversible) or 1 : 4 : 1 [if the equilibrium between (XXXIX) and (XLI) is established 4–5 times faster than the rate of formation of acetylene]. The experimental distribution is 4.4% C_2D_2, 77.1% C_2HD, and 18.5% C_2H_2, showing that reaction (3) does occur and, although reactions (1) and (2) predominate, the tetrahedrane (XL) and the bicyclobutyl radical (XLI) serve as precursors of the acetylenes. Thus the determination of the quantitative composition of the acetylenes suggests that the intermediate (or the transition state) may be the symmetrical tetrahedrane or the biradical from which the tetrahedrane can also be formed.

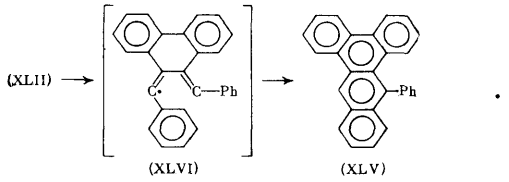
The dimerisation of acetylenes has been considered as another approach to the synthesis of tetrahedrane. In one of the first studies on these lines[66] it was shown that, when a mixture of acetylene and dideuteroacetylene is heated at 1200–1800 K, neither dimeric products nor HD are formed. The absence of deuterium exchange showed that tetrahedrane is not formed under these conditions.

However, Kandill and Dessy[67] reported in 1966 the possibility of the cyclisation of two acetylene groups into the tetrahedrane fragment. When 2,2′-di(phenylethynyl)-biphenyl (XLII) was photolysed or heated, an isomeric compound was obtained to which the structure of the tetrahedrane (XLIII) or the cyclobutadiene (XLIV) was attributed on the basis of the ultraviolet spectra:



(XLII) (XLIII) (XLIV)

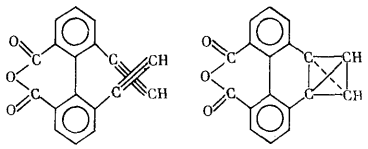
This structural assignment aroused a considerable controversy in the literature. White and Sieber[68] showed initially that the isomer obtained by Kandill and Dessy[67] is 9-phenyldibenzo[*a*,*c*]phenanthrene (XLV), which may be formed from the intermediate biradical (XLVI). Photolysis of compound (XLII) under different conditions and its subsequent thermolysis at 100°C did not lead to the formation of any compound other than (XLV):



(XLVI) (XLV)

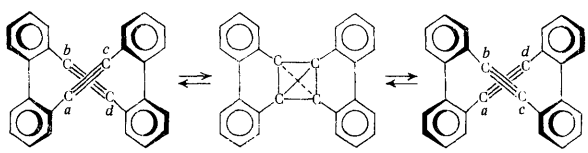
When compound (XLII) was heated at 150°C, compound (XLV) was again obtained together with unidentified compounds having high melting points and resembling phenanthrene according to their ultraviolet spectra. On the other hand, substances indicating at least the intermediate formation of tetrahedrane were not obtained in either thermal or photochemical processes.

Another diacetylene—6,6′-diethynyldiphenic anhydride (XLVII)—proved to be very stable under the conditions of pyrolysis (180°C) and photolysis[69]. No products, including those which might indicate the formation of the corresponding tetrahedrane (XLVIII), were found.



(XLVII) (XLVIII)

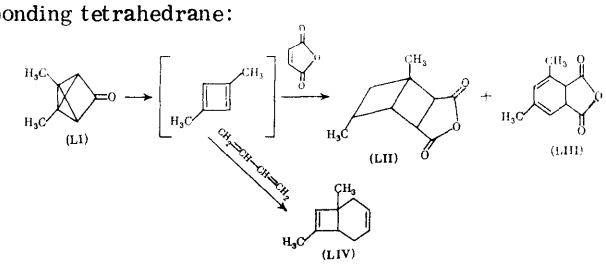
Nevertheless the idea of the possibility of synthesising tetrahedrane from acetylenes was not abandoned by investigators. For example, Staab and coworkers[70,71] undertook the synthesis of 9,10,19,20-tetradehydro[*a*,*c*,*g*,*i*]cyclododecene (XLIX)—a macrocyclic compound with crossed triple bonds in which structural factors favour the transannular interaction of the triple bonds. The possibility of such interaction was demonstrated by a number of chemical transformations, which justified the hypothesis that the acetylenic linkages are fairly close to one another. In order to confirm the possible formation of the tetrahedrane (L) from the diacetylene (XLIX), the authors[70,71] attempted to resolve the latter into enantiomers A and B and to detect the corresponding structural isomer which might have been formed by the irradiation of compound (XLIX) as a result of the transitions (XLIXA) ⇌ tetrahedrane ⇌ (XLIXB):



(XLIXA) (L) (XLIXB)

It was not possible to demonstrate the occurrence of photoracemisation, because the attempt to resolve compound (XLIX) into enantiomers chromatographically was unsuccessful. The authors[70,71] believe that the intermediate cyclobutadiene structure is preferable, but the problem whether it is formed from compound (XLIX) or via the tetrahedrane (L) remains open.

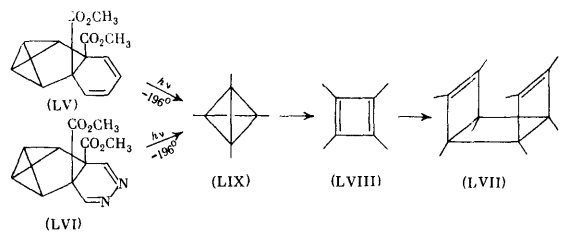
Yet another of the possible pathways to the synthesis of tetrahedrane was discovered by Masamune and coworkers[72], who investigated the thermolysis and photolysis of tricyclo[2,1,0,$0^{2,5}$]pentan-3-one. Thermolysis of the dimethyl derivative (LI) at 105.7° C gave very low yields of a mixture of compounds $C_{12}H_{16}$ (*m/e* 160), whose structures were not determined. Heating of compound (LI) in the presence of two equivalents of maleic anhydride was accompanied by the decomposition of the initial substance at a constant rate and led to the formation of compounds (LII) and (LIII). At a lower temperature (90°) only compound (LII) was detected; on heating, it rearranges to compound (LIII). When compound (LI) was treated with butadiene, a 30–40% yield of only 1,7-dimethylbicyclo-[4,2,0]octa-3,7-diene (LIV) was obtained. On the basis of the composition of the products and the finding that the rate of decomposition of compound (LI) remains constant regardless of the presence of a "trapping agent", the authors[72] proposed a mechanism involving 1,3-dimethylcyclobutadiene as an intermediate and not the corresponding tetrahedrane:



(LI) (LII) (LIII) (LIV)

At the same time an attempt was made to investigate the composition of the photolysis products of compound (LI). It was irradiated with a high-pressure mercury lamp at 25° for 4 h until the attainment of 94% conversion of the initial compound. Acetylene (2%), propyne (6%), and butyne (2%) were found in the condensate collected at −190° C. By analogy with other studies, which were already discussed above, the authors[72] believe that the intermediate formation of tetrahedrane is probable in view of the presence of acetylene.

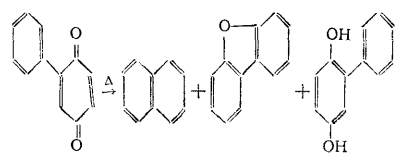
Polycyclic compounds (LV) and (LVI) have also been suggested as other tetrahedrane precursors containing the bicyclobutane fragment[73]. Photolysis of the diester (LV) in a matrix led to the formation of the cyclobutadiene dimer (LVII), but the authors[73] believe that the methyltetrahedrane (LIX) was formed as an intermediate and not tetramethylcyclobutadiene (LVIII), which could not be detected by infrared spectroscopy. It was suggested that the tetrahedrane isomerises to cyclobutadiene, which rapidly dimerises, the formation of the dimer (LVII) being faster than the valence [2 + 2] isomerisation (LIX) → (LVIII). As regards the transformation of the heterocyclic compound (LVI) owing to photolysis at 25° C, an analogous series of transformations [(LVI) → (LIX) → (LVIII) → (LVII)] was proposed on the basis of the composition of the products[73]:



(LV) (LVI) (LIX) (LVIII) (LVII)

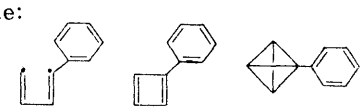
However, according to the literature[63], thermal isomerisation of tetrahedrane to cyclobutadiene is forbidden on symmetry grounds; the proposed mechanism is then incorrect.

Ions with the tetrahedrane structure have been detected in the mass spectra of certain compounds. For example, vacuum flash thermolysis (800° C) of phenyl-1,4-benzoquinone led to the isolation[74] of three substances: naphthalene (54%), 2-hydroxydibenzofuran (8%), and phenyl-1,4-hydroquinone (8%).



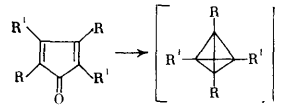
(LX) (LXI) (LXII) (LXIII)

According to the authors[74], naphthalene is formed via a stage involving the loss of two CO molecules from phenyl-1,4-benzoquinone and subsequent intramolecular stabilisation of the butadiene biradical (LXIV), cyclobutadiene (LXV), or the tetrahedrane (LXVI). This hypothesis is based on the fact that the mass spectra of 1,4-benzoquinones[75] contain the peak of the $C_4R_4^+$ ion, which is more likely to represent a tetrahedrane than a substituted cyclobutadiene:



(LXIV) (LXV) (LXVI)

The formation of the tetrahedrane structure (LXVII) has been observed[76] in the mass spectra also on fragmentation of substituted cyclopentadienols and cyclopentadienones:

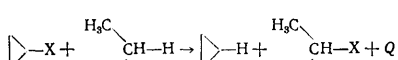


(LXVII)

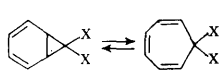
However, the determination of the exact structure of the ions in the gas phase by mass spectrometry is exceptionally difficult. A classical example is the controversy concerning the structure of the $C_7H_7^+$ ion to which the structure of the symmetrical propylium ion was attributed[77,78] on the basis of experiments with an isotope label, which was not confirmed by subsequent investigations[79,80]. Evidently the conclusion about the structure of ions of the type $C_4R_4^+$ and a reliable assignment of the tetrahedrane structure to the latter will become possible after a detailed investigation using the ion-cyclotron resonance technique[81].

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Thus, despite the considerable efforts by both theoreticians and experimenters, the problem of tetrahedrane has not been solved. Furthermore, the main question whether or not tetrahedrane can exist as a stable (metastable) species remains obscure. Strictly speaking, the unsuccessful attempts at synthesis cannot be regarded as proof of the instability of the compound, and the history of organic chemistry confirms this[82]. Here one may note two approaches to the experimental solution of the problem. The first involves the fixation of tetrahedrane in a matrix and the demonstration (for example by spectroscopy) of its structure or its generation in the gas phase and direct (for example by electron diffraction) demonstration of its structure. In the second approach, tetrahedrane derivatives containing substituents capable of specific stabilisation of the tetrahedrane molecule are to be synthesised. The substituents can be selected on the basis of the following considerations, in the discussion of which valuable comments have been made by Prof. P. v. R. Schleyer. On the one hand, the stabilising effect of the substituents on the three-membered ring may be estimated by considering the heat of the following "isodesmic"[83,84] process:



Unfortunately the available literature, thermochemical data do not allow a broad comparison. On the other hand, data for certain "isodesmic" equilibria may serve as the starting point. As an example, one may quote the electrocyclic equilibrium of the norcarane (LXVIII) and cycloheptatriene (LXIX) structures. If the substituent X stabilises the three-membered ring specifically, then the equilibrium should be displaced to the left relative to X = H; if the substituent causes destabilisation, the shift should be to the right. Examination of the experimental data shows that the parent hydrocarbon (X = H) exists almost wholly in form (LXIX)[85,86], while the dicyano-derivative (X = CN) exists exclusively in form (LXVIII):



(LXVIII) (LXIX)

Thus the presence of cyano-groups should presumably stabilise the tetrahedrane skeleton (particularly bearing in mind the potential possibility of the ready protonation of tetrahedrane; see above). Furthermore tetracyanotetrahedrane would be of interest as a member of a class of nitrogen–carbon compounds (tetracyanomethane, tetracyanoethylene, and percyanoadamantane; for a systematic account of percyano-compounds, see Makhon'kov[87]), but consideration of this and related problems is outside the scope of the present review.

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