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PHOTO AND THERMAL REACTIVITY OF HALOGENOCYCLOHEXADIENONES IN CHARGE TRANSFER COMPLEXES AND IN THE SOLID STATE

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Abstract - This article is a brief survey on studies found in the literature on the development of photoreactive and thermal processes of halogenocyclohexadienones in organized media.

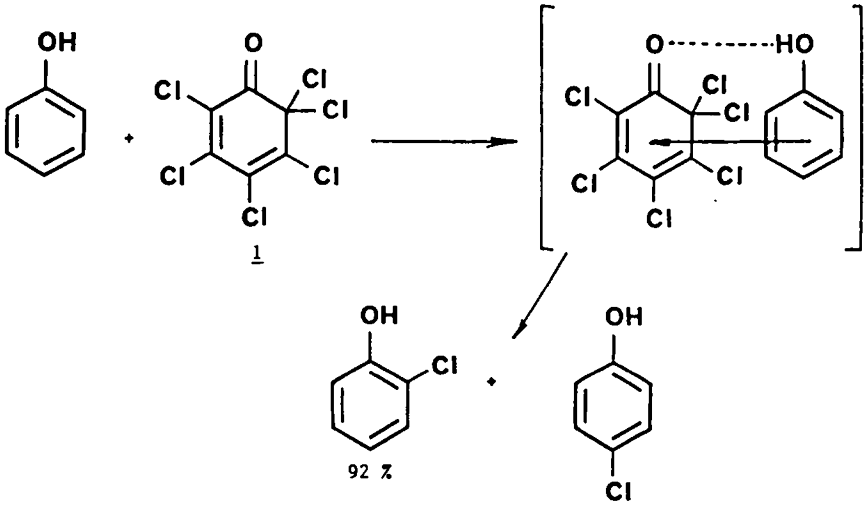
Cyclohexadienones belong to the class of compounds known as "blocked aromatic molecules"[1,2], that is, compounds in which the presence of a single tetrahedral atom prevents the molecules from conversion to aromatic molecules. They are of two types : ortho-dienones of type A or cyclohexa-2,4-dien-1-ones, and para-dienones of type B or cyclohexa-2,5-dien-1-ones. The numbering of the atoms in these molecules is as follows:

Cyclohexadienones are directly related to phenolic molecules. They have been the subject of general reviews in different fields of organic chemistry : rearrangements of cyclohexadienones[1,2,3], mechanisms of photochemical transformations[4], preparation and synthesis[5], electrophilic chlorinations of aromatic substrates[6,7].

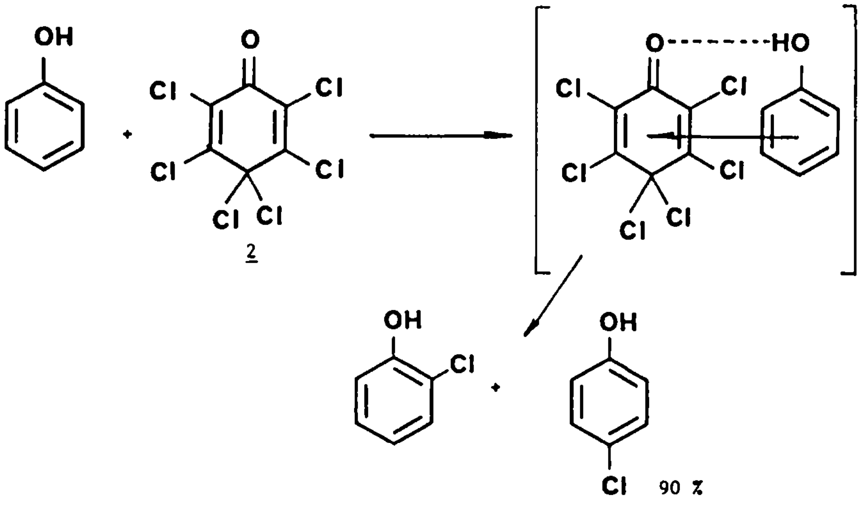
The present contribution reports studies found in the literature which deal with reactive *halogenocyclohexadienones* or *halogenodienones* when implicated in *organized media*. Halogenodienone designates a cyclohexadienone in which at least one halogen atom is borne by the tetrahedral atom. This implies that one aliphatic halogen-carbon bond is present in the molecule. The halogen can be a bromine (Br), a chlorine (Cl) or a fluorine (F). When the halogenodienone is activated thermally or photochemically, the aliphatic halogen-carbon bond breaks allowing the molecule to become aromatic. Due to the *anisotropy of organized media* characteristic behaviour of the dienone is observed and brings new insights into the various systems. These systems are presented in the following sections.

SECTION 1. REGIOSPECIFIC CHLORINATIONS OF AROMATIC SUBSTRATES.

An efficient regiospecific route for the chlorination of phenol, naphthol, and derivatives involving hexachlorocyclohexadienones has been reported[8,11]. The selectivity is attained by using a reagent tailored in such a way that it is able to participate in *donor-acceptor and H-bonding interactions*[8-10]. For example, when an equimolecular mixture of phenol and 2,3,4,5,6,6-hexachlorocyclohexa-2,4-dien-1-one 1 is irradiated in carbon tetrachloride at 5°C for 10 hrs with a 100 W Hanovia mercury lamp, o-chlorophenol is obtained in 92% yield, with p-chlorophenol being obtained in only 8% yield[8].



The reaction of an equimolecular mixture of phenol and 2,3,4,4,5,6-hexachlorocyclohexa-2,5-dien-1-one 2 in dimethylformamide for 72 hrs at 20°C gives a mixture of products with p-chlorophenol predominating[8].



The formation of a donor-acceptor complex and H-bonding interactions is necessary. This is shown by the fact that the selectivities of the chlorinations depend on the substrate (electronic and steric effects) and on the polarity of the solvent (ion-pairing effects)[9,10]. When the donor-acceptor complex is activated by irradiation, the chlorine-carbon bond breaks. Due to the proximity of the phenolic substrate, the released chlorine atom reacts with the proximate center leading to the desired selectivity. This proposition was also suggested to the authors by the observation that various attempts to crystallize complexes between 1 and 2 with phenol failed[12]. The whole process can be seen as a *selective transfer of a chlorine* from a chlorodienone, which acts as a *chlorinating agent*, to the phenol, which acts as a substrate.

It is noticeable that the system described in this section presents selectivities higher than that of other described models : chlorinations by N-chloroacetanilides[13], in micelles[14], in the presence of cyclodextrin[15]. It becomes apparent that the ability to design reactive systems by directing molecular interactions *prior* to chlorination is an efficient tool for planning new models and matrices for directing selective chlorinations involving substrates other than phenol and its derivatives.

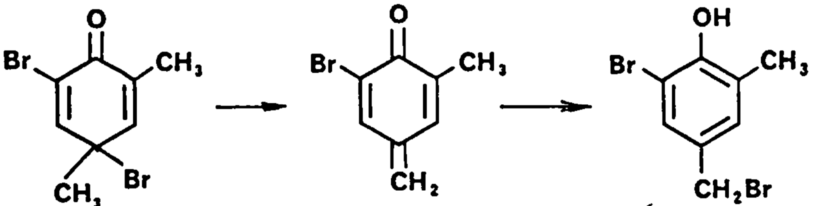
SECTION 2. REACTIVITY OF HALOGENODIENONES IN THE SOLID STATE.

The 2,4,6-tribromo-3,4-dimethylcyclohexadienone 3 has been observed to rearrange in the solid state to give exclusively 2,6-dibromo-4-bromomethyl-3-methylphenol 4[16-18].

3 4

Compound 3 is stable for some days at room temperature. In due course, however, it rearranges autocatalytically and presumably homolytically in the solid phase[16]. Purified samples are stable for longer periods (30 days and more)[17].

A similar reaction is reported to occur for 4,6-dibromo-2,4-dimethylcyclohexa-2,5- dienone 5, which rearranges spontaneously in the solid state into 6-bromo-4-bromomethyl-2-methylphenol 6[19]. An addition-elimination sequence involving a quinone methide is the most likely pathway of rearrangement[19].



5 6

No further investigations on the rearrangement of compounds 3 and 5 in the solid state have been pursued. The X-ray determination of the structures of these compounds and some kinetic studies of their transformations in the solid state are of interest in the precise determination of the mechanisms occurring in the crystalline or solid phase.

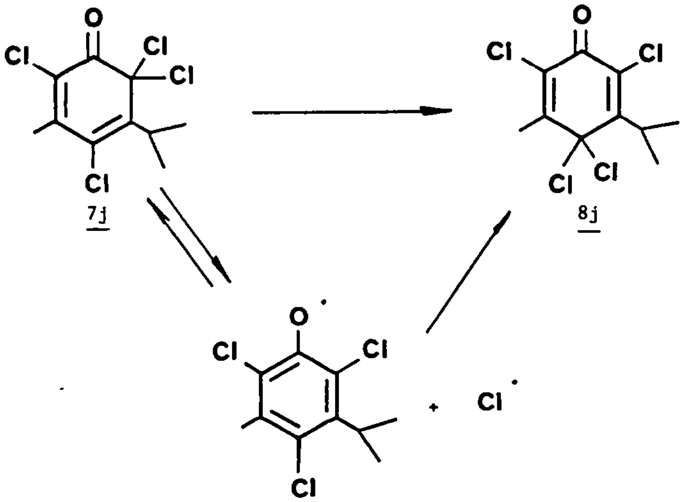
In a series of studies on the chlorination of phenolic compounds, the transformation in the solid state of a series of orthochlorodienones (o) 7a-j into the para isomers (p) 8a-j by heat or light has been reported[20-27].

7a-J 8a-J

	R1	R2	R3	R4	R5	Ref.
a	tBu	tBu	H	tBu	H	20
b	tBu	tBu	H	Me	H	20
c	Br	Br	H	Br	H	21
d	Br	Br	Me	Br	Me	21
e	Br	Br	Br	Cl	Br	21
f	Br	Br	Br	Br	Br	21
g	Cl	Cl	Cl	Me	Cl	22
h	Cl	Cl	Me	Me	Cl	22
i	Cl	Cl	Me	Cl	Me	23
j	Cl	Cl	Me	Cl	i-Pr	24-26

These transformations have been mentioned mostly in the experimental sections of the cited papers[20-24]. No mechanism was investigated except for the solid state transformation of ortho-chlorodienone 7j into parachlorodienone 8j. This transformation has been investigated in detail.

The transformation in the solid state of 2,4,6,6-tetrachloro-3-methyl-5-isopropylcyclohexa-2,4-dien-1-one 7j into 2,4,4,6 tetrachloro-3-methyl-5-isopropylcyclohexa-2,4- dien-1-one 8j is known to occur by uv irradiation or by heating[24-26]. From microscopic observations of single crystal transformations of 7j under uv irradiation and from thermal experiments, the solid state mechanism was concluded to be *homogeneous*[25-27] as defined by Curtin and Paul[28]. ESR signals were observed during the thermal transformation of powders and single crystals of 7j[25]. A *phenoxy radical* intermediate was identified[25]. The following scheme was proposed elsewhere[29]:



The mechanism of the reaction was rationalized on the basis of the crystalline structure of 7j[29,30]. As shown in Figure I, the distance between one chlorine attached to the C-6 position of a molecule of 7j and the C-4 position of a neighbouring molecule is 4.6 Å. Therefore, a chlorine atom can be easily transferred. In agreement with the topological disposition, *it is assumed that a radical chlorine atom migrates along the C-4...C-6 direction*[25]. Such a migration is made possible by the free space between the chlorine atom and the position to be reached[27].

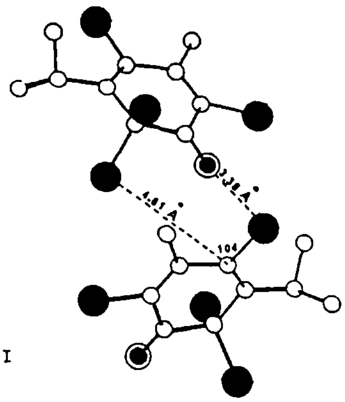


Figure I

This space was evaluated by the use of the Gavezzotti"s method[31]. Figure II shows a Di map at z = 0.32.

In addition, application of the Caillet and Claverie method to crystal 7j provides a model[32]. By elongation of the C-Cl bond, the new position of the molecules shows that the chlorine radical comes nearer to the C-4 position of the neighbouring molecule as shown in Figure III[27].

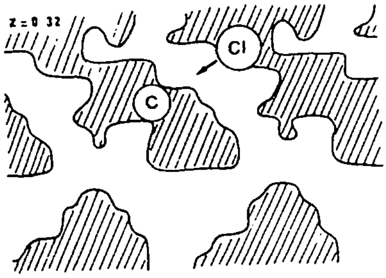


Figure II

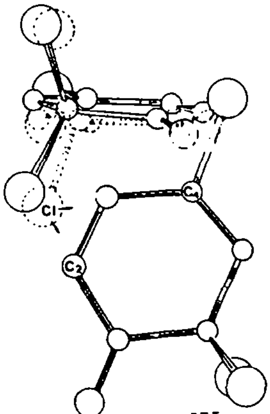
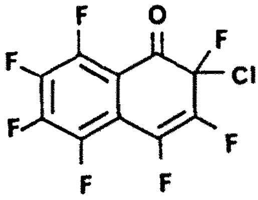


Figure III

This theoretical approach to a reaction mechanism in the solid state can be regarded as a molecular motion picture at the beginning of the reaction. This approach has been developed for other crystalline systems[33,34]. It is similar to studies reported by Bürgi and Dunitz, who proposed chemical reaction pathways from X-ray analysis[35].

A similar rearrangement has been observed during the heating of compounds 9 and 10 with Celite in a sealed tube[36].



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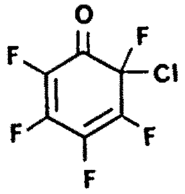

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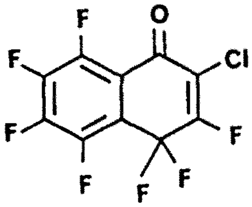
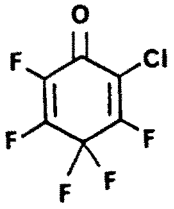
During these reactions, a fluorine atom is transferred from the ortho position to the para position to produce 9a and 10a.



9a

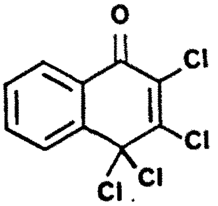


10a

From these results, it is easily deduced that a fluorine atom migrates preferentially to a chlorine which, in turn, migrates preferentially to a bromine. This order of migration may be explained by electronic factors as well as steric effects due to crystal packing.

SECTION 3. PHOTOCHROMISM OF α-AND β-TKN

Photochromism refers to compounds which change color when subjected to light and revert to their original color in the dark. Reported in 1899, the reversible photochemical transformation of 2,3,4,4-tetrachloro-1-oxo-1,4- dihydronaphthalene 11, or β-TKN, into a colored species was probably one of the first examples of solid state photochromism investigated[37]. From that discovery, studies on the mechanism of the process showed that photochromism of β-TKN 11 is related to crystal form and was assumed to be caused by a *physical change* of the irradiated system[38,39]. In 1962, from investigations of the photobehaviour of β-TKN 11 and its isomer 2,2,3,4-tetrachloro-1-oxo-1,2-dihydronaphthalene 12, or α-TKN, in carbon tetrachloride at room temperature and in a glassy frozen state (α-TKN is not photochromic in the solid state), it was deduced that the photochromism of β-TKN 11 in the solid state and in solution and of α-TKN 12 in solution maybe considered as a *reversible photochemical reaction*[40,41]. The authors proposed that the absorption of the light by the keto group induces a dissociation of the excited molecule into a chlorine atom and an aroxyl radical[40].



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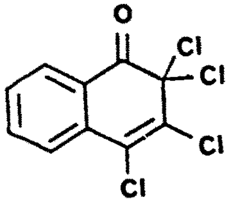

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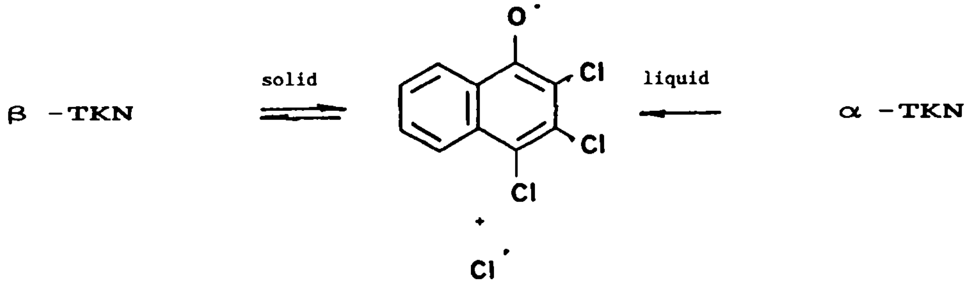
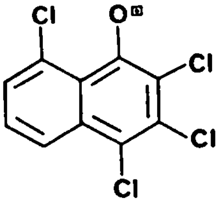


During this process a chlorine atom is released from the tetrahedral carbon, and the resulting 2,3,4-trichloronaphthoxylradical is responsible for the red coloration[40]. In order to obtain more information on the photochemical behaviour of β-TKN 11, its crystalline structure was determined at -160°C[42]. However, no explanation was given for the photochromic mechanism of β-TKN 11 in the crystal. ESR studies on irradiated powdered samples showed spectra characteristic of randomly oriented triplet radical pairs, in agreement with the chemical mechanism given previously[40]. The triplet ESR signal of β-TKN 11 was detectable by irradiation of solid samples with selected wavelengths > 313nm[43]. In the same paper, according to kinetic results in the solid state and in carbon tetrachloride, the photochromism of β-TKN 11 was explained as being due to the formation of a triplet state of the undissociated molecule[43]. Zweegers and Varma[44] have investigated the ESR spectrum of irradiated single crystal β-TKN 11. They showed that the triplet spectrum of β-TKN 11 is dependent on the orientation of crystals with respect to the magnetic field[44]. Concordance with the crystallographic geometries permitted the authors to assume that the triplet arises from unpaired electrons located on two neighbouring molecules along the principal z-axis separated by 4.8 Å. The nature of the radical pair is depicted *by a chlorine atom eliminated after excitation from one molecule which adds to the neighbouring molecule* as two unequal radicals[44]. Because of the environment, the released chlorine atoms add to the carbon nearest to the original position to give the second radical represented:



In a following communication, the same authors investigated the photochemical behaviour of isomer α-TKN 12[45]. Although α-TKN 12 resembles β-TKN 11 in its photoreactions in solution, it does not show photochromism in the solid state[45]. From X-ray analysis of α-TKN 12, it was concluded that the geometric arrangement of α-TKN 12 molecules in the crystal must inhibit the formation of the photochromic species[45]. ESR experiments at 77K with a 1000W superlight pressure Hg lamp with selected wavelength $260 < \lambda < 400$ nm produced an intense doublet ($g = 2$). It was concluded that the liberated chlorine atom from α-TKN 12 does not attack the neighbouring molecule in the crystal as it does in the β-TKN 11 crystal[45]. From this observation, since no color is generated even though the formation of the trichloro-1-naphthoxy radical is probable, the assignment of the photochromic behaviour of β-TKN 11[46] is unclear. In a following paper, the same authors investigated the solid state reactivit of two non-photochromic modifications of β-TKN 11[46]. Irradiation of the two modifications with uv light ($260 < \lambda < 400$ nm) at 77 K gives a doublet signal in the ESR spectrum similar to that observed for crystalline α-TKN 12[46]. All the results were accounted for by the assumption that the radical pairs generated by uv irradiation and the colored photoproduct cannot be identical[46]. In the last communication of the series, it was demonstrated by IR investigation of uv-irradiated solids and by SCF/LCAO π-electron calculations that a more convenient pathway involves a carbenium ion corresponding to a heterolytic cleavage of the chlorine-carbon bond[47]. *Steric hindrance* due to a short molecular oxygen-chlorine atom distance (2.973Å) in photochromic β-TKN 11 crystal was suggested to prevent fast recombination of the carbenium ion and chlorine anion[47]. The absence of such a short oxygen-chlorine distance in the two non-photochromic modifications of β-TKN 11 and in crystalline α-TKN 12 is in agreement with this proposal[47].

Whatever the mechanism, the investigation presented in this section shows that different molecular arrangements of α-TKN 11 and α-TKN 12 are involved in the photochemical reactivities of these compounds. Steric hindrance in the mobility of the chlorine atom in the lattice of the photoreactant crystals is one of the major factors permitting the observation of photochromism.

CONCLUSION

In this article we presented different behaviours of halogenocyclohexadienones when they are activated by heat or light in organized structures. Their main characteristic in organized assemblies is the ability to release a chlorine atom which can then react with the nearer active center. For instance, ortho- and para-dienones were used to design selective chlorinations. The selectivity was obtained by controlling the directionality of intermolecular forces between the two reacting partners. Very similar effects were observed during the transformations of an ortho-dienone into its para-isomer. In that case, by taking advantage of the solid state mechanism, the precise reaction mechanism was described at the beginning of the reaction. Moreover, *the use of theoretical calculations to provide models of the crystal are valuable because they show how the molecular forces which maintain the arrangement of the molecules in the crystal are implicated in the molecular process occurring in the solid phase.*

Topological arguments were also proposed to explain the discrepancy observed during the non-photochromic and photochromic behaviour of α-TKN and β-TKN in solution and in the crystal state. More precisely, β-TKN provided evidence of the molecular organization of the molecules necessary for the crystal to exhibit photochromism. The dependence of photochromism on the crystalline modifications of β-TKN is reminiscent of the crystal packing - dependent [2+2] photodimerization of cinnamic acid derivatives[48].

From a topological point of view, the studies reported here are directly related to two main problems:

i) due to topological constraints, any system describing a receptor entity (the crystal phase here) and the substrate molecule (the molecule which accepts a chlorine atom) gives geometrical information in the context of the topological sequence of events of systems leading to selective chlorinations of aromatic molecules. These systems are found in micelles[15], and in the presence of cyclodextrin[14], and in the presence of enzymes[49].

ii) more generally, the geometrical requirements for solid and organized systems may serve as prototypes for mechanistic studies of molecular contacts in solution reactions. They are of interest for labile systems involving the substitution of an aromatic ring by a chlorine atom at a specific position. These systems are found in pharmaceutics[50] and waste waters.

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