The Chemistry of Vicinal Polyketones

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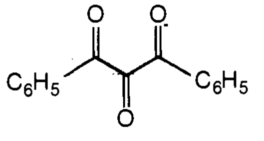
Contents

I. Introduction

de Neufville and von Pechmann,[1] reporting in 1890 on the first synthesis of diphenyl triketone (**1**), began in the following way: "Nachdem die Existenz-fahigkeit der 1,2-Diketonen nachgewiesen war, konnte man daran denken, einen Schritt weiter zu gehen und die Darstellung von Verbindungen zu versuchen, welche mehr als zwei, also zunachst drei benachbarte Carbonyle oder die 1.2.3-Triketogruppe -CO · CO · CO- enthalten." One year later, Abenius and Soderbaum[2] described diphenyl tetraketone (**2**), and in 1901 Sachs and Barschall[3] reported dimethyl triketone (**3**), the first aliphatic vicinal trione. Interest in the question of how many carbonyl groups may be juxtaposed and what will be the properties of the resulting vicinal polyketones has continued through the years.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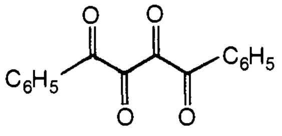
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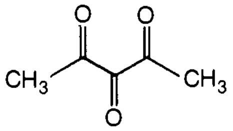
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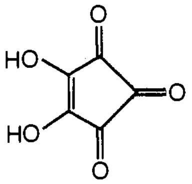
In fact, although their structures were established much later, croconic acid (**4**) was first reported by Gmelin[4] in 1825 and rhodizonic acid (**5**) by Heller[5] in 1837. Their oxidation products, leuconic acid (**6**) and triquinoyl (**7**), are often written in the attractive polyketone forms shown above, but the CO groups are fully hydrated in the solid state and partly hydrated in solution.[6] No polyketone containing more than four free, vicinal carbonyl groups has been reported although such compounds could certainly be capable of existence.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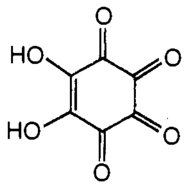
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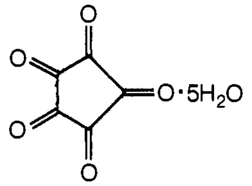
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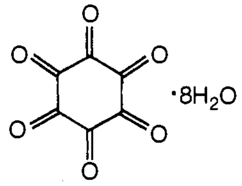
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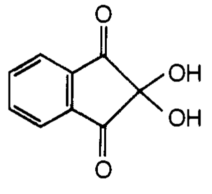
The best-known triketone derivative is ninhydrin (**8**), the monohydrate of indan-1,2,3-trione. This compound was first synthesized by Ruhemann[7,8] in 1910 who dis-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covered and correctly interpreted its most useful reaction with α-amino acids. The chemistry of ninhydrin was reviewed by McCaldin in 1960.

Except for the reviews of "oxocarbons"[6] and of ninhydrin chemistry,[9] no systematic survey of the chemistry of vicinal polyketones has appeared. The present review is an attempt to fill this gap and make the synthesis and properties of these compounds, at present scattered over more than 80 years of the chemical literature, conveniently available. We have endeavored to provide complete coverage of the literature on polyketones through mid-1973; relevant aspects of the chemistry of di- and polyketoesters, lactones, lactams, etc., are included, but a complete survey of such compounds has not been attempted.

II. Synthesis of Triketones

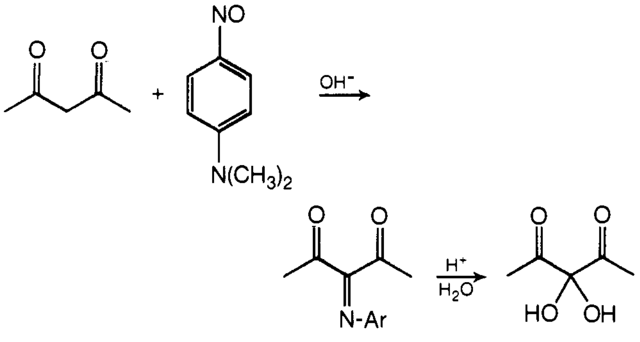
vic-Triketones and their hydrates are usually readily interconvertible (*vide infra*). Accordingly, no distinction will be made in the following discussion between synthetic methods which afford trione directly and those which produce hydrate.

A. From β-Diketones

The ready availability of β-diketones and the enhanced reactivity at their α position have made them the starting materials of choice for most syntheses of triones.

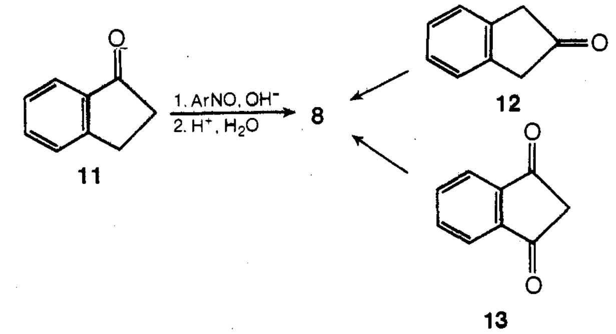
1. Sachs Procedure Using p-Nitrosodimethylaniline

The first synthesis[3] of dimethyl triketone (**3**) employed base-catalyzed condensation of *p*-nitrosodimethylaniline (toxic!) with acetylacetone to give the diketoimine **9** followed by acid hydrolysis to furnish the hydrate **10**. **3** was then obtained by distillation. This procedure was improved by Sachs and Rohmer[10] and appears to be the method of choice[11,12] for synthesis of dialkyl triketones. It has also been used[13] for synthesis of alkyl aryl triketones.

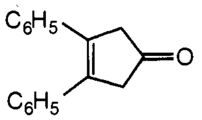


9 **10**

The original Ruhemann synthesis[7] of ninhydrin (**8**) from indanone (**11**) was intended to be a synthesis of 1,2-indandione which fortuitously gave the trione hydrate, albeit in poor yield. Subsequently, Ruhemann showed[14] that 2-indanone (**12**) and 1,3-indandione (**13**) could also be converted in poor yields to **8**. The other examples of coversion of mono- to triketones by this method are the recent syntheses[15a,b] of 1,2-diphenylcyclopentenetrione (**15**) from **14** in moderate yield and of 4,5-methylenedioxy- and 5,6-dimethoxyninhydrin.[15b]



11 **12** **13**



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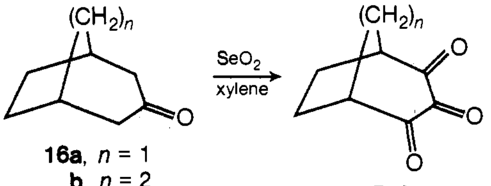
2. Selenium Dioxide Oxidation

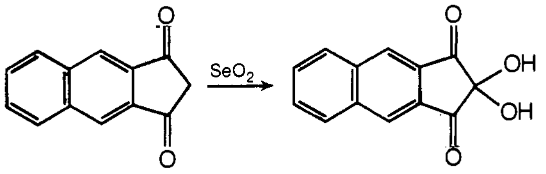
It is not surprising that extension of the well-known[16a,b] oxidation of monoketones to α-diketones with selenium dioxide was one of the first methods explored for synthesis of polyketones from mono- and diketones. In general, the results have been disappointing; yields are often low and in some cases unidentifiable products were obtained. The only two examples of direct conversion of mono- to triketones were reported by Alder and Reubke[17] who obtained 46% of **17a** and 27% of **17b** from the symmetrical, bicyclic monoketones **16a,b**.



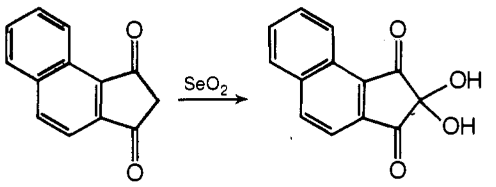
16a, $n = 1$
b, $n = 2$

17a,b

Examples of conversion of β-diketones to triketones include oxidation of acetylacetone to **3** (12–33% yield[11,18,19]), benzoylmesitoylmethane to phenyl mesityl triketone[20] (**18**, 26%), dimesitoylmethane to dimesityl triketone[21] (**19**), benzoyl-2-pyridoylmethane to phenyl 2-pyridyl triketone[22] (**20**), and 1-hydroxy-2-phenylcyclopentene-3,5-dione to 1-hydroxy-2-phenylcyclopentene-3,4,5-trione[15] (**21**, 50%). Applications to the synthesis of indantrione and related compounds include synthesis of ninhydrin (**8**) itself,[23] and the naphtho compounds **22** (23% yield[24]) and **23**[24] (53%). Analogous reactions with the appropriate anthracene derivatives afforded[24] the anthraquinones **24** and **25** which were unaffected by further treatment with selenium dioxide. The trione **26** was reportedly[25] obtained as yellow crystals (?) in unspecified yield from the corresponding β-diketone (but *cf.* ref 90).

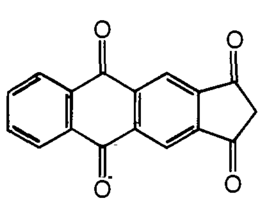


22 (23%)



23 (53%)

An unfortunate failure was isolation of a selenium con-



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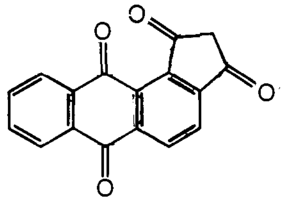

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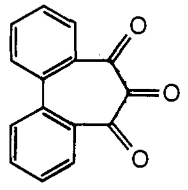

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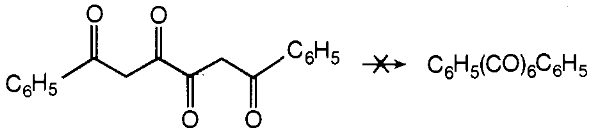
taining product from reaction[26] of 1,6-diphenylhexane-1,3,4,6-tetrone (**27**). Other failures include attempted



27

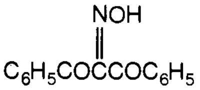
synthesis of diphenyl triketone[18] and of the tetrafluoro analog[27] of ninhydrin. In the latter case a dimeric product was obtained. No systematic study of any of these reactions has been undertaken and the erratic results observed are probably due in good part to variations in experimental procedures and lack of optimization. In spite of the convenience of direct conversion of mono- or diketone to trione with selenium dioxide, a number of superior procedures are available at present.

3. *Reaction with Oxides of Nitrogen*

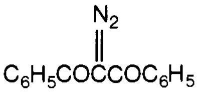
Shortly after the turn of the century, Wieland and Bloch[28] described the action of "nitrosen Gase," generated by reaction of arsenious oxide with nitric acid, on solutions of diaroylmethanes at −30° to give "isonitroso dimers" which liberated nitrous oxide upon warming and afforded triketone hydrates. The reactive species, proposed to be N_2O_3, was also generated[29] by the action of sulfuric acid on sodium nitrite. Horner and Maurer[30] used an equimolar mixture of NO and NO_2 for high yield synthesis of a wide variety of diaryl triketones. Triones were not obtained from acetylacetone[31] or benzoylacetone.[13]

By-products in these reactions include oximes and diazo ketones. Thus, dibenzoylmethane afforded[28] the 2-oxime (**28**), diphenyl triketone, and dibenzoyldiazomethane (**29**), while the diphenylhexanetetrone (**27**) gave appreciable yields of dioxime[32,33] **30** and bisdiazo tetraketone[33] **31** but no hexaketone.

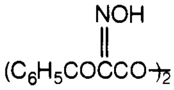
$$ArCOCH_2COAr + N_2O_3 \xrightarrow{-30^\circ} [\text{isonitroso dimer}] \xrightarrow{RT} Ar(CO)_3Ar{\cdot}H_2O + N_2O$$


$C_6H_5CO\overset{NOH}{\overset{\|}{C}}COC_6H_5$

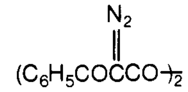
28


$C_6H_5CO\overset{N_2}{\overset{\|}{C}}COC_6H_5$

29


$(C_6H_5CO\overset{NOH}{\overset{\|}{C}}CO\text{—})_2$

30

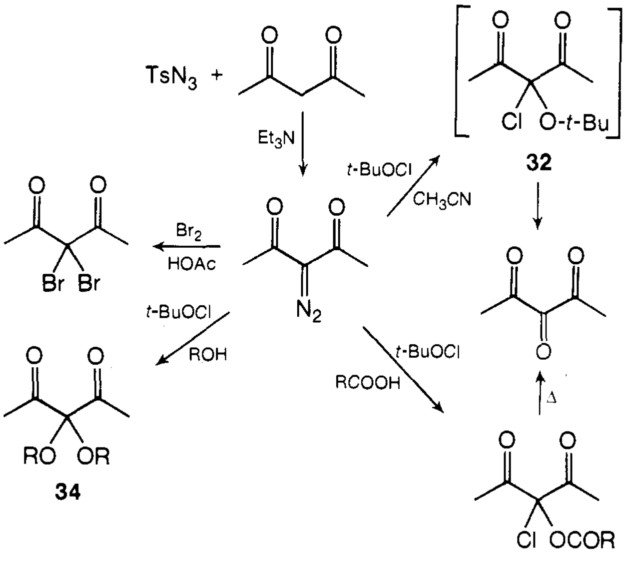

$(C_6H_5CO\overset{N_2}{\overset{\|}{C}}CO\text{—})_2$

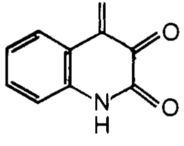
31

The nature of the reagent in these reactions is not clear, particularly since N_2O_3 is in equilibrium with NO and NO_2. It has been reported[34] that conversion of diethyl malonate to diethyl oxomalonate is more convenient with NO_2 than the earlier "Organic Syntheses" procedure[35] using the Wieland and Bloch method. The opposite claim is made[36] for reaction of ethyl acetoacetate. Structures of intermediates have also not been established, and it is not clear what significance, if any, should be attached to observations[28a,36] that **28** and ethyl α-nitrosoacetoacetate are converted by N_2O_3 to the corresponding carbonyl compounds. In spite of the lack of mechanistic understanding, the mild conditions and simplicity of operation make the Wieland–Bloch procedure an attractive one for polyketone synthesis.

4. *Via α-Diazo β-Diketones*

The "diazo transfer reaction" reviewed by Regitz[37] provides an efficient method for synthesis of α-diazo β-diketones. These compounds react with a variety of substrates to give monosubstituted β-diketones, some of which can be converted to triones. More important, they react with *tert*-butyl hypochlorite in a variety of media, as summarized below, to provide diaryl, alkylaryl, and cyclic triones or their hydrates in nearly quantitative yield.[38] Thus, reaction in dry acetonitrile leads directly to triketone, possibly *via* the intermediate **32** shown, and reaction in formic or acetic acid solution affords chloro esters **33** which lose acyl chloride at 160–170° and again give free triketones. The ketals **34** resulting from reaction of diazo diketone with *tert*-butyl hypochlorite in alcohol solution (chloro ethers may also form[38c]) are readily hydrolyzed to give trione hydrates. This method has also been applied[39] for synthesis of quinisatin (**35**).





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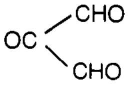

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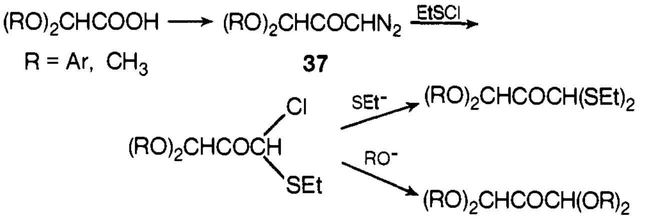
A number of bisketal and bisthioketal derivatives of mesoxaldehyde (**36**) have been synthesized[40] from the diazo ketone **37** using ethyl sulfenyl chloride in place of *tert*-butyl hypochlorite.

Recently Regitz and Geelhaar[41] reported the synthesis



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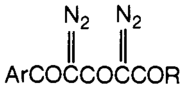


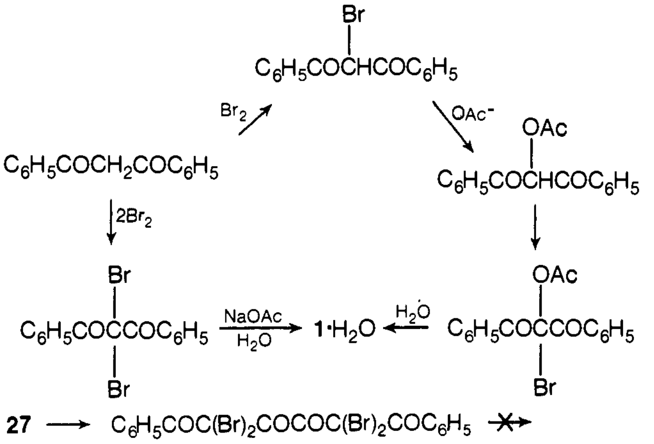
$\mathrm{ArCO\overset{N_2}{\overset{\|}{C}}CO\overset{N_2}{\overset{\|}{C}}COR}$

38

of a number of bis(diazo) triketones (**38**). It remains to be seen if these compounds will prove to be precursors of the still unknown vicinal pentaketones.

5. *Via Bromination of β-Diketones*

The de Neufville and von Pechmann synthesis[1] of diphenyl triketone (**1**) referred to in the Introduction involved bromination of dibenzoylmethane, replacement of the bromine atom by acetate, and repeat bromination followed by hydrolysis to give the hydrate of **1**. The method has also been used[30] for synthesis of di-β-naphthyl triketone. Bigelow and Hanslick[42] described a variation in which dibenzoylmethane is dibrominated and then both bromine atoms are replaced. Careful purification is necessary in order to obtain bromine-free product by this procedure. In an attempted synthesis of diphenyl hexaketone (**40**) the intermediate tetrabromide **39** failed to react[32] with acetate; the dibromide of dimesitoylmethane was reduced to monobromide upon treatment with sodium acetate.[21]



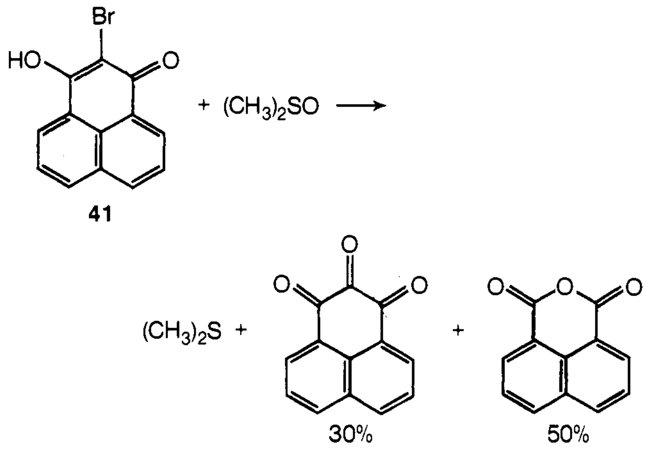
39

$C_6H_5(CO)_6C_6H_5$

40

It might be noted that α-bromo β-diketones are convertible into reductones or their derivatives[1,43] (*vide infra*), which can then be oxidized readily to polyketones.

Two recent reports describe extension of the use of dimethyl sulfoxide as an oxidizing agent for synthesis of triketones. Thus, the bromo compound **41** reacted[44] with DMSO to give 30% of 2*H*,3*H*-dihydrophenalene-1,2,3-trione (**42**) in addition to naphthalic anhydride. The second report,[45] from the patent literature, describes treatment of β-diketones with hydrogen bromide in DMSO at 50–70° followed by steam distillation from hydrochloric acid solution. An intermediate, possibly **43**, was observed.



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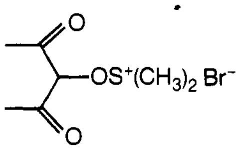
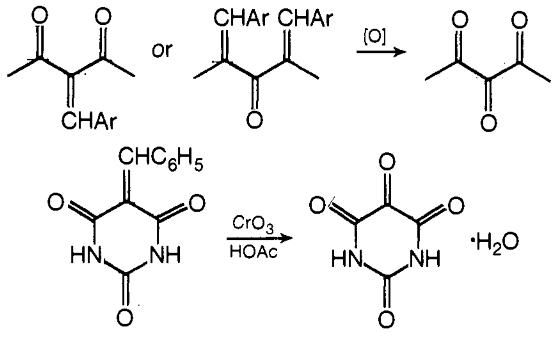


43

B. Other Methods

1. *Oxidation of Unsaturated Ketones*

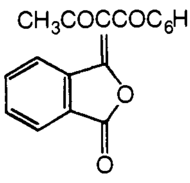
Mono- or bis(arylidene) derivatives of ketones are readily obtainable and can be converted to triones by suitable oxidation procedures. The most successful example is one of the "Organic Syntheses" procedures[46] for synthesis of alloxan hydrate (**45**) in which barbituric acid is condensed with benzaldehyde and the benzal derivative **44** oxidized with chromium trioxide in acetic acid. A similar procedure[23c] starting from 1,3-indandione (**13**) apparently gave ninhydrin (**8**).



44 45

A number of workers have employed ozonolysis of unsaturated carbonyl compounds. Thus, Harries obtained mesoxaldehyde (**36**, as polymer) from phorone[47] and from dibenzalacetone,[48] and Bernatek and Straumsgard[49] isolated the *p*-nitrophenylhydrazone of **36**, among other products, from ozonolysis of *p*-benzoquinone. Recently, Schill and coworkers achieved modest yields of bis(dodecyl) triketone[50] and a catenane trione[51] by low-temperature ozonolysis of substituted *p*-quinones using the dimethyl sulfide procedure for ozonide decomposition (earlier workers used work-up with water); they observed that hydroxylated dialkylquinones gave higher yields (25–28% as compared with 6%). The phthalide derivative **46** could be ozonized[52] to methyl phenyl triketone.

Attempted synthesis[53] of 5-methylcyclopentanetetrone by ozonolysis of the furfurylidene derivative **47** afforded only carbon dioxide. This failure may well be due to the



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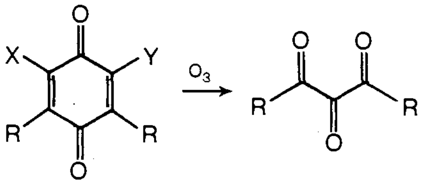
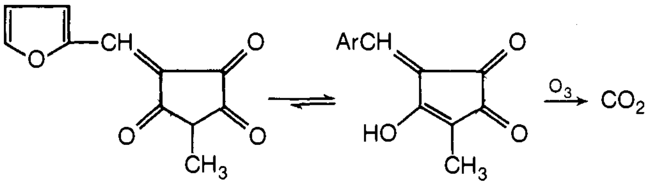


R = H, $C_{12}H_{25}$
X = Y = H
X = H; Y = OH
X = Y = OH

fact that **47** exists in enolic form(s) so that ring cleavage *via* ozonolysis of the enol(s) occurred. The enolic character of triacylmethanes has been exploited by Scheiber and Herold[54a,b] for trione synthesis. When one of the acyl groups is aromatic, enolization occurs predominantly in its direction, and ozonolysis (work-up with water) gave mainly a single trione.



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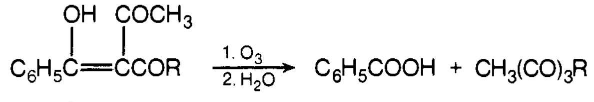


$$C_6H_5C(OH){=}C(COCH_3)COR \xrightarrow[2.\ H_2O]{1.\ O_3} C_6H_5COOH + CH_3(CO)_3R$$

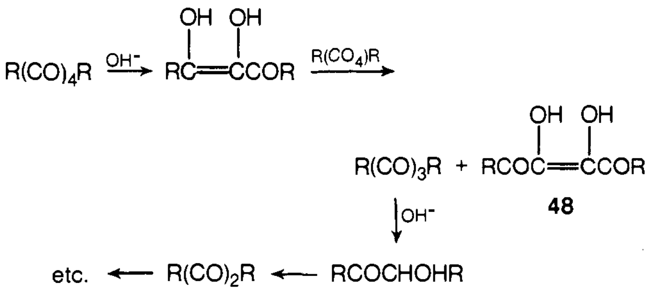
R = CH_3, C_6H_5

2. *Oxidation of Dihydro Polyketones (Reductones)*

Dihydro polyketones usually exist in enediol forms and are referred to as reductones; their chemistry was reviewed by von Euler and Eistert[55] in 1957 and by Schank[56] in 1972. These compounds are readily oxidized, a reaction of considerable biological interest. Reagents used for synthesis of polyketones include oxygen or air,[43a,b,57-60] chlorine in acetic acid,[61] sodium hypochlorite,[62] bromine water,[63-65] iodine,[22,43a,b,59,66-68] silver ion,[62,69] ferric ion,[70] nitric acid,[30,71-73] *p*-benzoquinone,[59,74,75] higher polyketones, selenium dioxide,[76,77] thionyl chloride,[78] and enzymes.[62,79] The use of copper ion with diphenyl reductones reportedly[78,80] results in loss of carbonyl group(s) and formation of benzil.

3. *From Tetraketones*

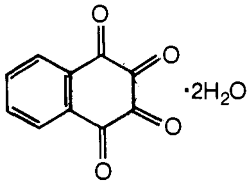
As will be discussed in the section on reactions of polyketones, these compounds undergo a base-catalyzed benzilic acid type of rearrangement (section VI.D) with subsequent loss of carbon dioxide to give reductones containing one carbon atom less than the starting polyketone. The resulting reductone is then oxidized by starting polyketone to give its reductone and a new polyketone containing one less carbonyl group. When the starting material is a tetraketone, the products are reduced tetraketone (**48**, "diacylformoin") and a trione. In most cases, this trione undergoes further reaction to give a



dione, etc. However, both dimesityl- (**19**) and di-*tert*-butyl triketones (**49**) are much less reactive than the corresponding tetraketones and can be obtained from them.[21,30,80] Ninhydrin is similarly more stable than tetralintetrone (**50**) and has been obtained from it.[81,82] It should be noted that only 50% conversion to triketone can be achieved unless an additional oxidizing agent is present.

t-Bu(CO)$_3$-*t*-Bu

49

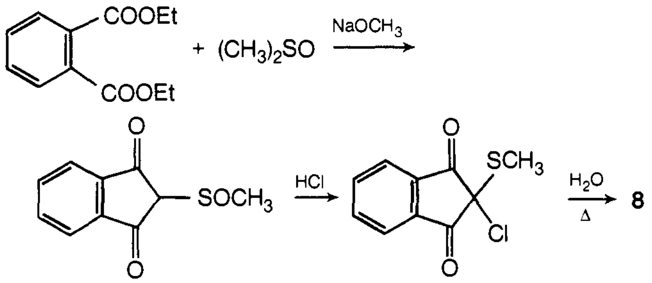


50

4. *Miscellaneous Synthetic Methods*

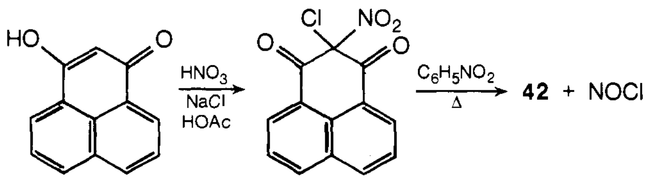
a. Using the Pummerer Rearrangement

Becker and Russell[83a,b] applied the Pummerer reaction[84] for synthesis of ninhydrin (**8**) in 80% overall yield from diethyl phthalate as shown below. Although no other applications of this method have been reported, it appears to be an attractive procedure for synthesis of cyclic triones.

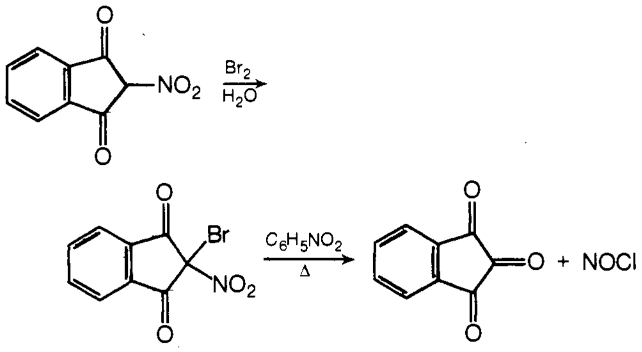


b. From *gem*-Halonitro Diketones

Two reports of this method have appeared. Ried, *et al.*,[85] treated 2-hydroxyphenalenone (**51**) with nitric acid and sodium chloride in acetic acid to obtain the chloronitro compound **52** which was then heated in nitrobenzene. Nitrosyl chloride was eliminated and 2*H*,3*H*-dihydrophenalenetrione (**42**, "perinaphthindanetrione") was obtained in about 50% overall yield. The bromonitro compound **53** was obtained by Wanag and Lode[86] *via* bromination of 2-nitroindandione and similarly afforded 43% of indantrione (**54**) upon thermolysis.



51 **52**



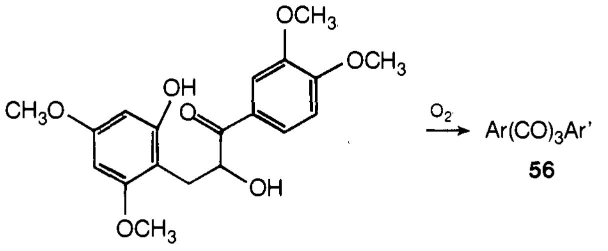
53 **54**

c. Lead Tetracetate Oxidation

Lead tetraacetate oxidation of acetylacetone gave[87] a *gem*-diacetate which was hydrolyzed to dimethyl triketone hydrate. Reaction of ethyl acetoacetate afforded a mixture of mono- and diacetates.

d. An Air Oxidation

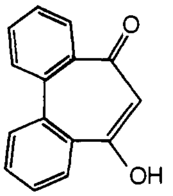
The α-hydroxy ketone **55** was reported[88] to yield triketone **56** upon long standing in solution in the dark in the presence of oxygen.



55

e. A Correction

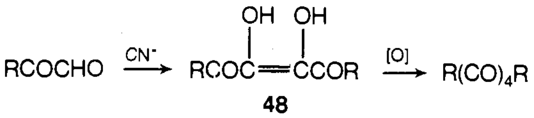
A report[89] that the trione **26** could be synthesized by oxidation of **57** with nitric acid in acetic acid was shown[90] to be incorrect. The product was, in fact, 9,10-phenanthrenequinone (**58**).



57

III. Synthesis of Tetraketones

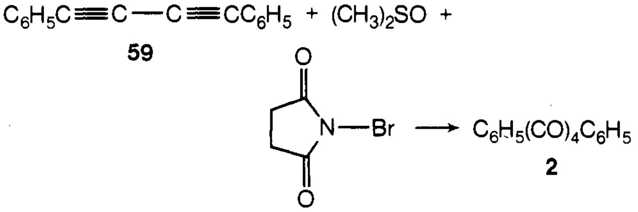
With the exception described below, tetraketones have been synthesized from their dihydro derivatives. Open-chain diaryl and di-*tert*-butyl tetraketones have been obtained by a procedure developed by Soderbaum and coworkers.[2,91,92] Self-condensation of α-keto aldehydes in the presence of cyanide ion affords the reductones, generally called diacylformoins (**48**), presumably in a manner analogous to the benzoin condensation. These are oxidized, most frequently with nitric acid (but *cf.* section II.B.2), to tetraketones, usually in good yield. Oxidation of *p*-dimethylaminoformoin was not successful,[73] probably because of concomitant oxidation of the activated aromatic ring. The only aliphatic compound reported is di-*tert*-butyl tetraketone; apparently synthesis of other dialkyl tetraketones has not been investigated although dialkylformoins are known.[93] All of these syntheses have produced symmetrical tetraketones. The only example of a crossed condensation is the synthesis[22] of 2-pyridyl phenyl triketone (**20**) by condensation of phenylglyoxal with 2-pyridinecarboxaldehyde followed by oxidation with iodine.



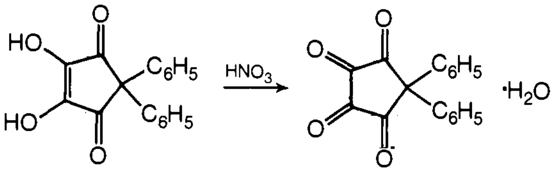
$$\mathrm{RCOCHO} \xrightarrow{\mathrm{CN^-}} \mathrm{RCO}\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}{=}\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}\mathrm{COR} \xrightarrow{[\mathrm{O}]} \mathrm{R(CO)_4R}$$

48

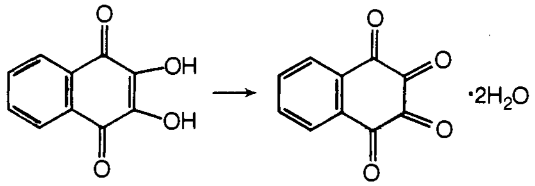
Wolfe, *et al.*,[94] recently described a new procedure for synthesis of α-diketones in which diarylacetylenes are treated with *N*-bromosuccinnimide in DMSO. This method has been used with diphenyl-1,3-butadiyne (**59**)to give a 62% yield of diphenyl tetraketone (**2**).



In addition to "oxocarbons," a few cyclic tetraketones have been synthesized, in all cases from dihydrotetrones. Thus, the cyclopentanetetrone **61**[95] was obtained from **60**; tetralintetrone (**50**)[11,61,62] and substituted tetralintetrones[62] were obtained from the appropriate 2,3-dihydroxy-1,4-naphthoquinones. The dihydrate of **50** has been given the trivial name "oxolene" and shown to have antiviral activity[96]; similar activity has also been observed[97] with certain triones.



60 **61**



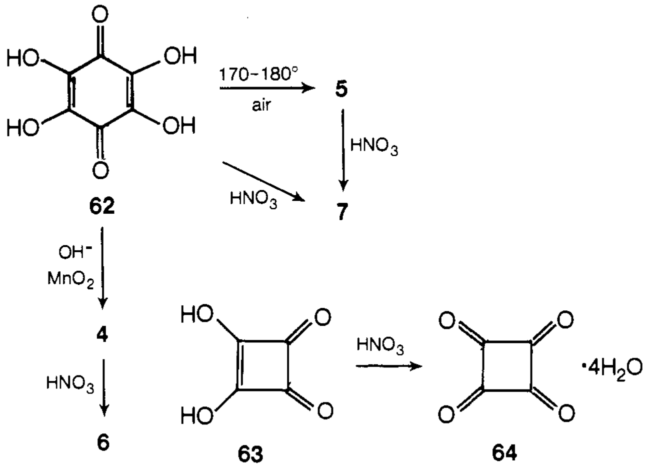
50

Dehydration of open-chain tetrone hydrates to free tetrones is more difficult than dehydration of trione hydrates. The cyclic tetraketones have only been obtained as hydrates.

IV. Synthesis of Oxocarbons

Since the chemistry of oxocarbons was reviewed by West and Niu[6] in 1970, these compounds are not covered in the present review. However, the following brief summary of the preferred method of synthesis is included for the sake of completeness. Fatiadi, Isbell, and Sager[98] have described reliable procedures (successfully repeated in the author's laboratory) for synthesis of croconic (**4**), leuconic (**6**), and rhodizonic (**5**) acids and for triquinoyl (**7**) using the same kinds of reactions as are described in preceding sections. It might be noted that **4** and **5** are commercially available.

The starting material is tetrahydroxy-*p*-benzoquinone (**62**) which is prepared from glyoxal. Oxidation of **62** with air at 170–180° yields **5** which is oxidized with nitric acid to **7**; **7** can be obtained directly from **63** with nitric acid. Reaction of **62** with sodium hydroxide in the presence of manganese dioxide results in ring contraction and oxidation to give **4**; further oxidation with nitric acid yields **6**. Commercially available squaric acid (**63**) can also be oxidized to "octahydroxycyclobutane" (**64**).[99]

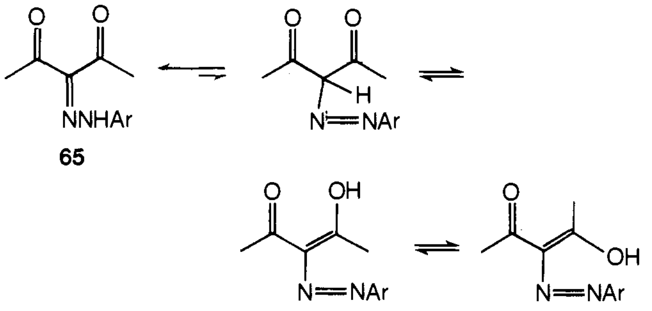


V. *Carbonyl Derivatives of Polyketones*

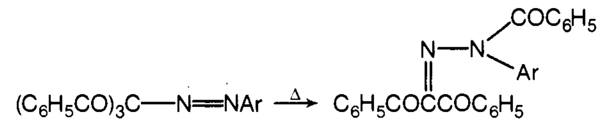
A. From Polyketones

Oximes, semicarbazones, arylhydrazones, quinoxalines, etc., can be prepared from *vic*-polyketones or their hydrates by the usual procedures. It is often possible to prepare monocarbonyl derivatives, and, in such cases, reaction usually occurs at a central carbonyl group. Comprehensive listing of derivatives will be found in the tables.

The structure of arylhydrazones has been the subject of some question. These could exist, *a priori*, as the hydrazono tautomer **65** or a variety of azo tautomers, all involving some type of hydrogen bonding. The spectroscopic properties[19,100-102] of some such derivatives have been examined and indicate that **65** is the correct structure.



Substituted phenylazotribenzoylmethanes (**66**) undergo[103] thermal rearrangement in the solid state to give *N*-acylarylhydrazones (**67**) of tricarbonyl compounds. X-Ray crystallographic analysis of two such hydrazones has been reported.[104]



$$(C_6H_5CO)_3C{-}N{=}NAr \xrightarrow{\Delta} C_6H_5CO\overset{\overset{\displaystyle N{-}N(COC_6H_5)Ar}{\|}}{C}COC_6H_5$$

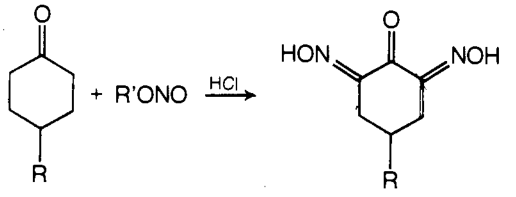
66 **67**

B. From Compounds Containing Fewer Carbonyl Groups

The procedures described below result in synthesis of oximes and hydrazones from compounds which are not *vic*-polyketones. In fact, as can be seen from the tables, many polyketones are known only in the form of such derivatives. Satisfactory methods for converting these derivatives to polyketones would make a variety of interesting compounds available.

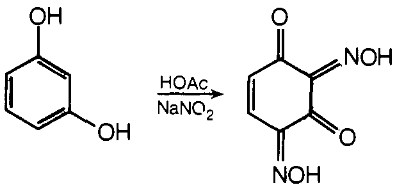
1. Oximes

When the classical procedure for formation of α-oximino ketones (isoamyl nitrite, hydrochloric acid) was applied to cyclohexanone and 4-methylcyclohexanone by Batesky and Moon,[105] good yields of dioximes (**68**) of cyclohexanetrione were obtained. This procedure, or use of nitrous acid, has been applied to a number of β-diketones; the most striking case is the synthesis[32] of the 2,5-dioxime (**30**) of diphenyl hexaketone from the tetrone **27**.

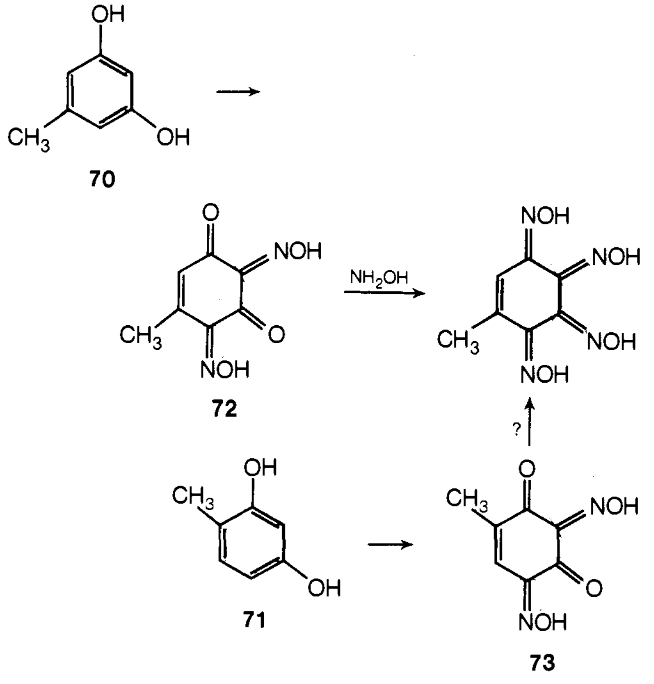


68

Resorcinol undergoes bis-oximation to give the 1,3-dioxime (**69**) of cyclohexenetetrone. Orcinol[110] (**70**) and cresorcin[111] (**71**) gave isomeric dioximes (**72, 73**) of methylcyclohexenetetrone. **72** was converted to the tetraoxime by reaction with hydroxylamine; conversion of

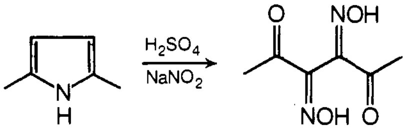


69

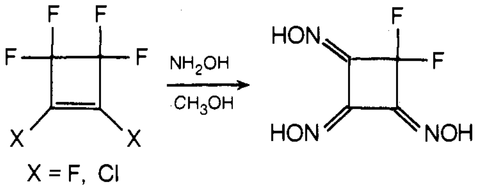


73 to tetraoxime, which would have confirmed the relationship of **72** and **73**, was not reported.

Two additional reactions are worthy of note: first, the conversion[112] of 2,5-dimethylpyrrole (**74**) to dimethyl tetraketone 3,4-dioxime (**75**) by nitrous acid; second, reaction of the perhalo compounds **76** and **77** to give trioximes.

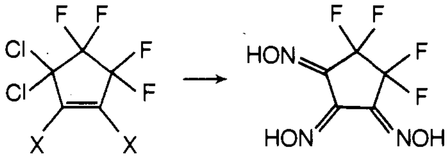


74 **75**



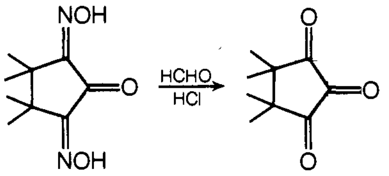
X = F, Cl

76

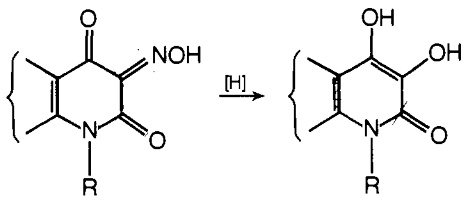


77, X = F, Cl

Two examples of conversion of oximes to ketones by N_2O_3 were mentioned earlier (section II.A.3). Diphenyl triketone monoxime (**28**) has also been converted to trione hydrate with nitrous acid although the authors stated[1] that the method was unreliable, and a similar method has been used for di-*p*-tolyl tetraketone.[92] The only report of a simple hydrolytic cleavage is the work of Ingold and Shoppee[114] who obtained tetramethylcyclopentanetrione (**79**) by reaction of the dioxime **78** with formaldehyde and hydrochloric acid.



78 **79**

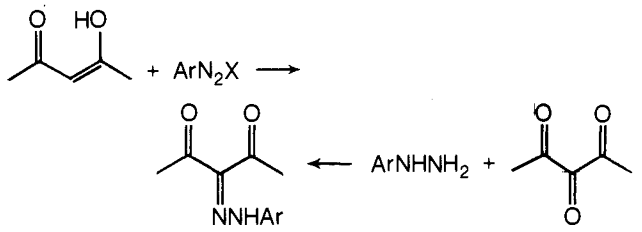


80 **81**

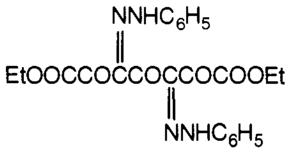
Reduction of oximes with stannous chloride[70] or catalytically[115] has been used with heterocyclic oximes **80** to yield the reductones **81** which can then be oxidized to trione.

2. *Aryl Hydrazones by Diazo Coupling*

The coupling of aromatic diazonium salts with phenols and enols is a well-known reaction which was reviewed[116] in 1959. The reaction occurs readily with enolic *β*-diketones[117] and has often been used for characterization of such compounds. The products of diazo coupling with *β*-diketones and of arylhydrazine reactions with polyketones have been shown to be identical in a number of cases. Diazo coupling thus provides a convenient procedure for obtaining arylhydrazones of many polyketones as is apparent from the very large number of such derivatives in the tables. Thus, for example, the bis(phenylhydrazone) (**82**) of diethyl pentaketopimelate has been obtained from the triketo ester by Mullen and Crowe.[118]



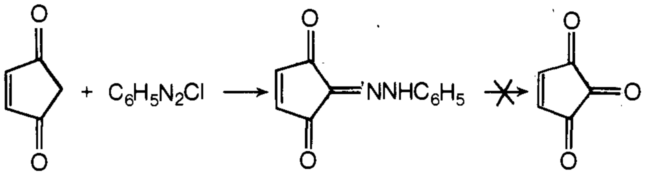
$EtOOCCOCH_2COCH_2COCOOEt + C_6H_5N_2Cl \longrightarrow$



$$EtOOCCO\overset{NNHC_6H_5}{\overset{\|}{C}}CO\underset{NNHC_6H_5}{\underset{\|}{C}}COCOOEt$$

82

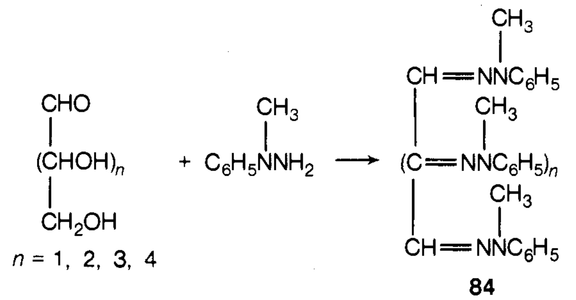
No examples of conversion of these hydrazones to free ketones have been recorded. Depuy and Wells[119] investigated exchange with formaldehyde, levulinic acid, etc., and hydrolytic methods in an unsuccessful attempt to prepare cyclopentene-3,4,5-trione (**83**) from the 4-phenylhydrazone.



83

3. *Alkazones*

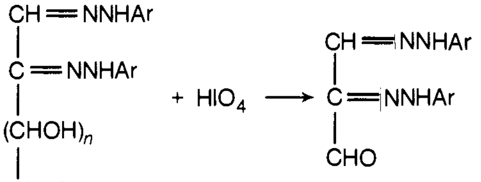
It is well known that reaction of aldoses and ketoses with excess phenylhydrazine results in formation of osazones. The fact that this reaction stops after introduction of two hydrazono groups has been attributed to stabilization by hydrogen bonding in the osazone. Chapman and coworkers[120] reasoned that replacement of hydrogen by a methyl group would eliminate this stabilization and allow reaction to proceed further. In fact, reaction of sugars with 1-methyl-1-phenylhydrazine proceeded under mild conditions (acetic acid–ethanol–water at room temperature) to give permethylphenylhydrazones (**84**) for which the name alkazones was suggested. Thus fructose furnished the *N*-methyl-*N*-phenylalkazone of hexaketohexane.



84

4. Other Phenylhydrazone Forming Reactions

Two oxidative procedures can be mentioned in this connection. Chargaff and Magasanik[121] and later El Khadem et al.,[122] treated sugar osazones with periodic acid to obtain bis(arylhydrazones) (**85**) of mesoxaldehyde.



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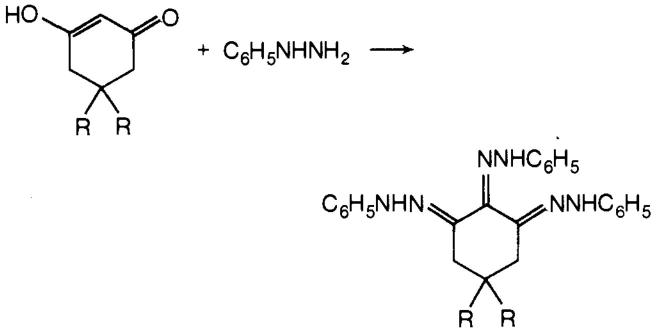


86

Eistert, *et al.*,[123] observed that 1,3-cyclohexanedione and 5-alkyl substituted compounds reacted with excess phenylhydrazine in acetic acid to give tris(phenylhydrazones) (**86**) of 1,2,3-cyclohexanetriones. The reaction of cyclohexanedione was investigated in detail by Fatiadi.[124]

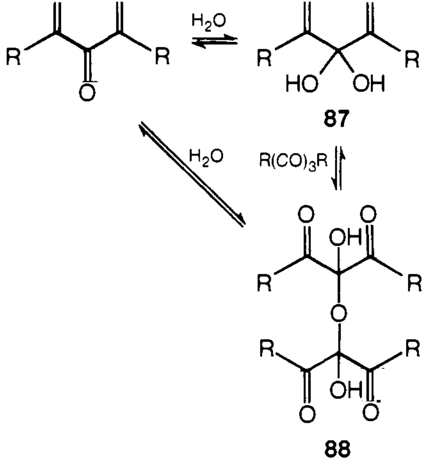
VI. Reactions of Polyketones

The reactions of *vic*-polyketones can be characterized as the chemistry of the highly activated carbonyl group. This enhanced reactivity is due in good measure to destabilization of polyketones because of the unfavorable electrostatic interaction between adjacent, dipolar carbonyl groups. Cyclic compounds, in which these carbonyl groups are eclipsed, are particularly reactive since they cannot achieve the partial relief of such interactions which is permitted to open-chain compounds. It is not surprising that preferential reaction at a central carbonyl group is usually observed since the maximum number of vicinal carbonyl interactions are relieved in this way.

A. Hydration

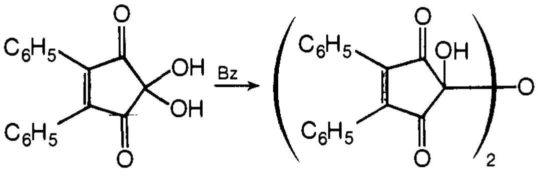
The hydration of polyketones is readily apparent when these highly colored substances are allowed to stand in air. Within a relatively short period of time the color begins to disappear as they combine with atmospheric moisture to give the colorless (trione) or light yellow (tetrone) hydrates. Since many procedures for synthesis of polyketones involve aqueous medium at least as part of work-up, the hydrates are the usual products obtained. They can be converted to the free polyketones by procedures such as distillation, sublimation, heating over phosphorus pentoxide at reduced pressure, treatment in an inert solvent with molecular sieve, phosphorus pentoxide, or thionyl chloride, etc. The broad melting ranges and color changes observed during melting point determination clearly derive from dehydration during heating.

The inference, originally based on visual evidence, that hydration occurs at a central carbonyl group was later confirmed by spectroscopic data. Although the simple *gem*-dihydroxy structure **87** has generally been accepted as the correct representation of these hydrates, recent evidence suggests that the situation is more complicated. Yamazaki, *et al.*,[15] obtained a monohydrate of diphenylcyclopentenetrione (**15**) which afforded a hemihydrate upon recrystallization from benzene; the structure **89** was suggested on the basis of infrared evidence. Other reports of trione hemihydrates have appeared.[17,125,126] Nye, *et al.*,[126] examined the nmr spectrum of a hemihydrate of diphenyl triketone and found that integration supported a structure (**88**, R = C_6H_5) with four phenyl groups per two hydroxyls rather than the 2:2 ratio predicted for **87**. It seems likely, particularly in the presence of limited amounts of water, that the initial hydrate can react with an unhydrated molecule to give the hemihydrate **88**.



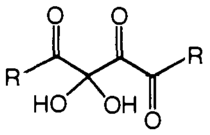
87

88



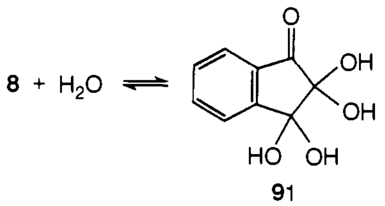
89

Structures of hydrates of tetraketones have also been assumed to be of the simple *gem*-diol type (**90**); the presence of an α-diketo moiety can be observed in the absorption spectra.[30,73] The unsymmetrical nature of the hydrate (**90**, R = *tert*-butyl) of di-*tert*-butyl tetraketone is apparent from the fact that two *tert*-butyl resonances are observed[127] in the nmr spectrum of the hydrate in contrast to the single sharp line in the spectrum of di-*tert*-butyl tetraketone.



90

Dihydrates of tetraketones have also been reported but without any precise information about structure. The dihydrate (**91**) of ninhydrin is written as 1,1,2,2-tetrahy-

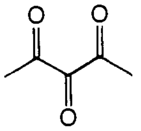


91

droxyindan-3-one. The problem of the structure of the oxocarbons **5**, **7**, and **64** was mentioned briefly in the Introduction. The infrared spectra of these compounds in the solid state show only hydroxyl absorption, indicating clearly that they are perhydroxycycloalkanes. However, when **5** and **7** are dissolved in anyhydrous solvents, yellow solutions with ultraviolet absorption above 350 nm result. Attempts to obtain completely unhydrated compounds have only resulted in decomposition.

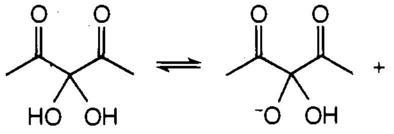
A number of qualitative generalizations have been made concerning rates and equilibria of hydration. Steric effects are important as illustrated by the fact that unhydrated di-*tert*-butyl and dimesityl triketones can be isolated directly from aqueous media. Cyclic triketones, such as indantrione (**54**), in which the unfavorable interaction between adjacent carbonyl groups is maximal, hydrate more rapidly than open-chain triones, and the equilibrium constant for hydration is larger. Operation of electronic effects is suggested by Horner and Maurer's[30] statement that hydration occurs more readily with diaryl triketones having electron-withdrawing para substituents than with those bearing electron-supplying groups. These authors[73] also note that dehydration of diaryl tetraketones is more difficult than for analogous triketones.

Unfortunately, very little quantitative data on rates or equilibria of hydration are available. Preliminary results from the author's laboratory[31] using a combination of spectrophotometry and gas chromatography to study hydration of diphenyl triketone (**1**) in dioxane–water show that the rate of hydration is relatively slow at low water concentrations and that the equilibrium constant for hydration of **1** has the value of approximately 30 M^{-1} at 25° in dioxane and decreases at higher temperatures. The only detailed quantitative study reported is the work of Knoche, *et al.*,[128] on hydration of indantrione (**54**) to ninhydrin (**8**). Pure **8** was dissolved in anhydrous dioxane and the relative concentrations of **8** and free water were determined by nmr spectroscopy. The equilibrium constant for the reaction **54** + $H_2O \rightleftharpoons$ **8** under these conditions (spectrometer probe temperature unspecified) was 55 M^{-1}; the value extrapolated to pure water was 3×10^3 M^{-1}. The equilibrium constant for hydration of **8** in dioxane–water was found to be 0.31 M^{-1} using the aromatic region of the nmr spectrum for analysis. The authors used a pressure jump method to determine relaxation times (τ) for the hydration reaction. The value of $1/\tau$ was pH dependent (general base catalysis) and varied between 1.7 and 41 sec^{-1}. It should be noted that the possibility of base-catalyzed decomposition of **8** or **54** was not considered. The behavior of **54** in sulfuric acid has been investigated by MacFayden[129] using absorption spectroscopy. In sulfuric acid of specific gravity 1.80 the only specie present was **54**; at specific gravity 1.54 only ninhydrin (**8**) and mixtures of both were found at intermediate water concentrations.



$$+ H_2O \rightleftharpoons \text{hydrate} \qquad K_{\text{hydr}} = \frac{[\text{hydr}]}{[\text{trione}][H_2O]}$$

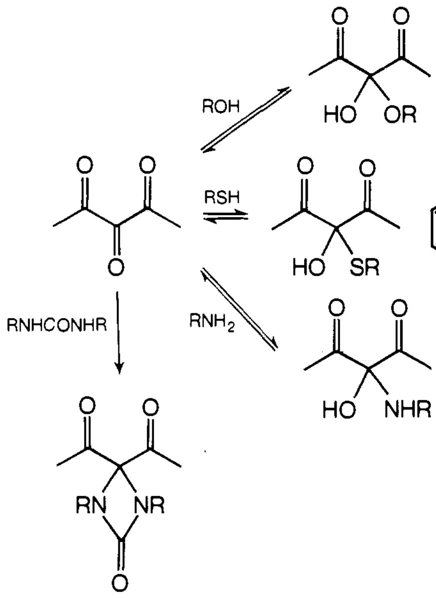
Polyketone hydrates are generally stable in the solid state. It should be emphasized that in solution the hydrates are in equilibrium with polyketone and any chemistry observed may be that of either specie. A further complication in solution is due to the acidity of hydrates (the pK_A of ninhydrin has been calculated[129a,b] to be 8.6 from polarographic data). The anion **101** is an intermediate in the benzilic acid rearrangement of triones (*cf.* section VI.D), and solutions of hydrates may not be stable for appreciable periods of time, especially at elevated temperatures or in polar solvents. Some of the anomalies observed in the chemistry of polyketones probably derive from failure to consider this possibility.

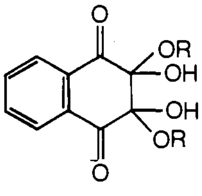


101

B. Reaction with Alcohols, Thiols, and Amines

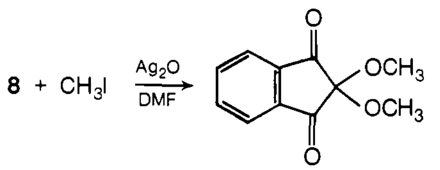
The high reactivity of polyketones with water is also observed with a variety of other compounds which undergo uncatalyzed addition to a central carbonyl group. Recrystallization from alcohol solution of 2*H*,3*H*-dihydrophenalenetrione (**42**) gave crystalline hemiketals[44] and of tetralintetrone dihydrate (**50**) gave bis(hemiketals)[61] (**92**).





92

Other hemiketals have not been isolated, but there is no doubt that alcohol solutions of polyketones contain very little free polyketone. Ketals can be obtained by reaction of α-diazo-β-diketones with *tert*-butyl hypochlorite in alcohol (*cf.* section II.A.4). Ninhydrin (**8**) has been converted[131] to dimethyl ketal **93** by reaction with methyl iodide in the presence of silver oxide. The same workers reported obtaining an isomeric, orange ketal **94** when indantrione (**54**) was treated with dimethyl sulfite and hydrochloric acid in methanol solution.



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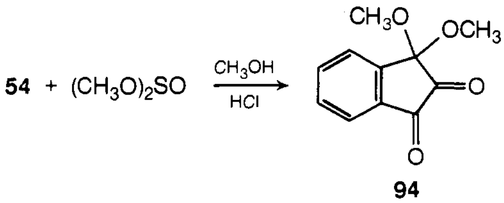
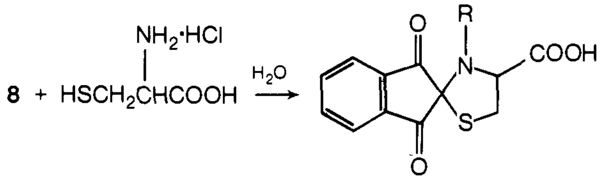


94

The reaction of thiols parallels that of alcohols. Thus **54** reacts with ethyl mercaptan to give a hemithioketal[132] and with ethanethiolamine hydrochloride to give the amine hydrochloride of the hemithioketal.[133] Reaction of **8** with cysteine hydrochloride afforded the spiro product **95**;[134a] earlier workers[134b] had assigned a fused ring structure.



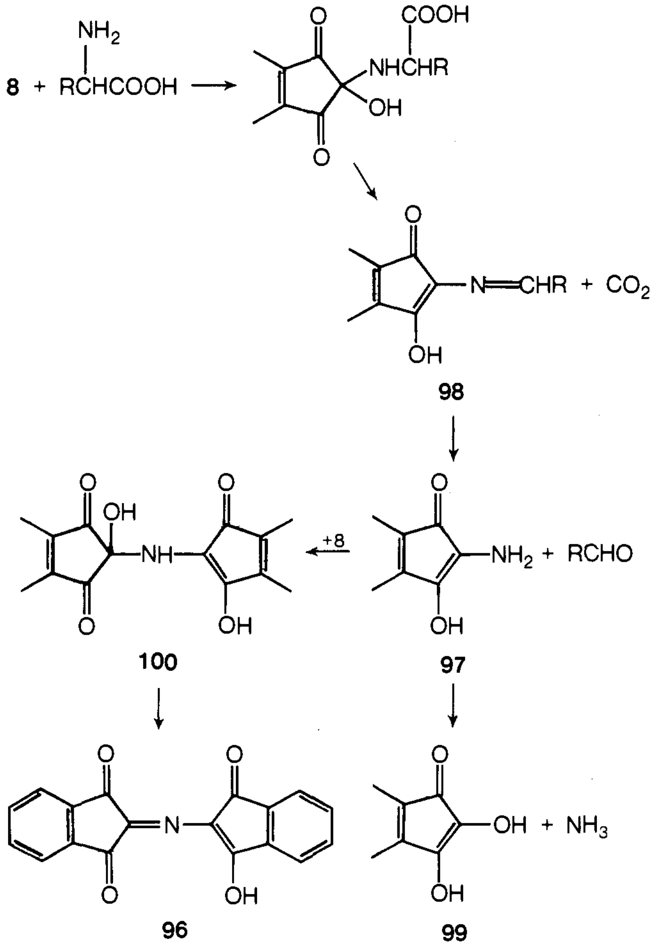
95

Reactions of amines with polyketones and their hydrates, particularly **8**, have been investigated in some detail in connection with the ninhydrin color test for amino acids (section VI.C). A number of uncatalyzed additions leading to *gem*-carbinolamines have been reported. These include reaction of **42** with aromatic amines[135,136] and ureas[135,137] (to give ureides), of diphenyl triketone and ninhydrin with amidrazones,[138] and of ninhydrin with aromatic[139] and cyclopropylamines.[140] It has been suggested[139] that reactions of amines with ninhydrin involve S_N2 displacement of a hydroxyl group by amine; reaction of amine with the indantrione present in equilibrium is a possible alternative.

C. Reaction with Amino Acids

The reaction (pH ~5, 100°) of ninhydrin with amino acids to form Ruhemann purple (**96**) provides a standard method for quantitative analysis.[141] The historical development of Ruhemann's discovery has been interestingly summarized by West,[7] McCaldin[9] reviewed the chemistry of ninhydrin in 1960, and a review by Yuferov[142] on mechanism has appeared recently.

SCHEME I



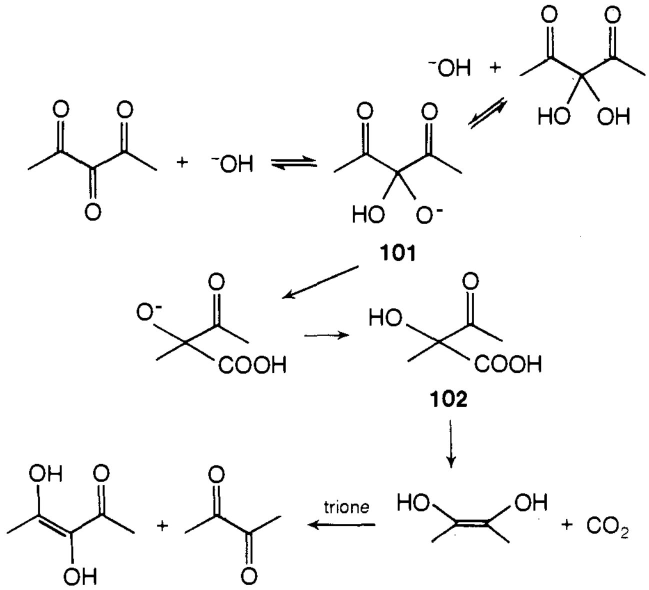
The overall reaction was correctly interpreted by Ruhemann who also isolated the intermediate aminoreductone **97**. The mechanism outlined by McCaldin[9] is summarized briefly in Scheme I. Detailed discussion is beyond the scope of this review although it is clear that some of the details of mechanism could use additional support. Recent work relating to mechanism has appeared[143-145] including two reports by Yuferov, *et al.*,[146] describing esr signals detected during reaction of **8** with amino acids. It was stated that the esr spectra obtained were characteristic for specific amino acids. These results may be due to a minor by-path; the McCaldin mechanism above makes no provision for free radical intermediates.

There is no reason, *a priori*, why other triketones should not react with amino acids in a manner analogous to ninhydrin. In fact, colored products which appear to be analogs of Ruhemann purple have been observed in reactions with tetramethylcyclopentanetrione hydrate (**79**), the benzoninhydrins[24] **22** and **23**, 2*H*,3*H*-dihydrophenalenetrione[147a] (**42**), and a diketolactam.[147b] Colored products are also obtained by reaction of ninhydrin with amines[139,140] and a wide variety of nitrogen-free compounds.[148] In certain cases ninhydrin may act as a reducing agent; for example, it reacts[149a] with the 2-oxime of indantrione to give **96** and a product of oxidative ring cleavage. Thiocyanate ion also reacts[149b] with **8** to give **96**.

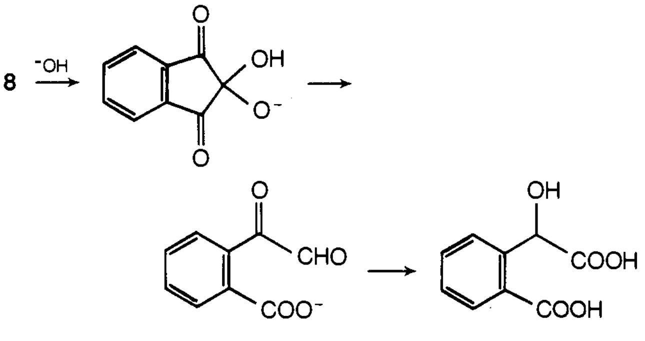
A variation of the ninhydrin test using fluorescence analysis has recently been reported by Udenfried and coworkers.[150]

D. Benzilic Acid Rearrangement

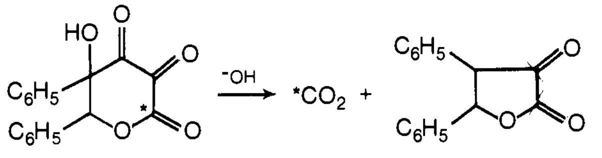
vic-Polyketones and their hydrates undergo a facile reaction in basic solution which appears to be analogous to the benzilic acid rearrangement of α-diketones. Addition of hydroxide ion to a central carbonyl group of polyketone or reaction of weakly acidic hydrate with hydroxide gives the oxy anion **101** which rearranges with acyl group migration to β-keto-α-hydroxy acid **102**. This intermediate has been isolated from base-catalyzed reactions of diphenyl triketone[1] and of alloxan[151a,b] (**45**). Decar-



boxylation of **102** is followed by oxidation of the intermediate acyloin (from triketone) or reductone (from tetraketone) by starting material to give one molecule of reduced starting material and one of a compound having one carbonyl group less than the starting material. The latter product can then undergo further reaction. Compounds such as ninhydrin (**8**) in which acyl migration would lead to cyclobutane derivatives undergo cleavage by base. Melkonian and Holleck[152] studied the reaction of **8** polarographically and determined activation parameters.



The central carbon atom of triketones is eliminated as carbon dioxide in the mechanism shown above. This point has been investigated using carbon-14 labeling in the reactions of diphenyl triketone,[153] ethyl α,β-diketobutyrate,[154] quinisatin[115] (**35**), alloxan[151b] (**45**), and the diketolactone[155] **103.** The first three compounds behaved as expected; **45** and **103** did not. In the case of **45**, the result was explained on the basis of preferential migration of an amide group; the results with **103** were explained by assuming initial hydrolysis to an acid **104** which undergoes usual β-ketoacid decarboxylation and subsequent disproportionation, cyclization, etc.



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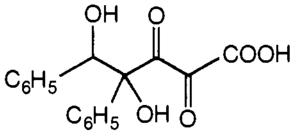
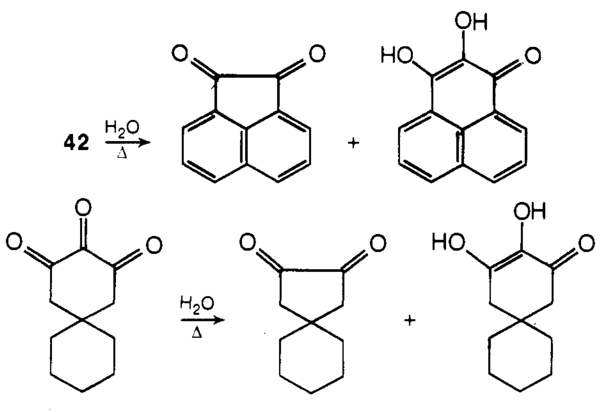


104

Hydrates are sufficiently acidic to form the anion **101** and undergo uncatalyzed reaction simply upon heating in aqueous solution. Conversions of tetralintetrone to ninhydrin plus isonaphthazarin and of dimesityl and di-*tert*-butyl tetraketones to triones have already been mentioned. Additional examples include reaction of dihydrophenalenetrione[44,156] (**42**) hydrate and the spiro compound[82] **105.**

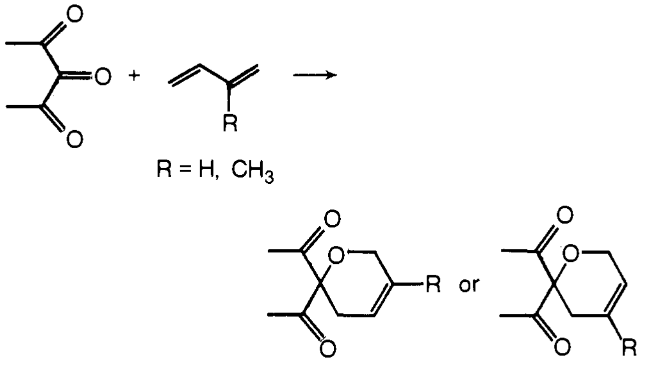


105

Similar rearrangements also occur upon acid catalysis. Diphenyl triketone reacted with aluminum chloride[153,157] or sulfuric acid[157,158] in benzene to give benzil, and **42** was reported[159] to behave similarly. Some of this work has not been reproducible.[153] Sodium azide in concentrated sulfuric acid has also been reported[160] to lead to cleavage of **42** and **45.**

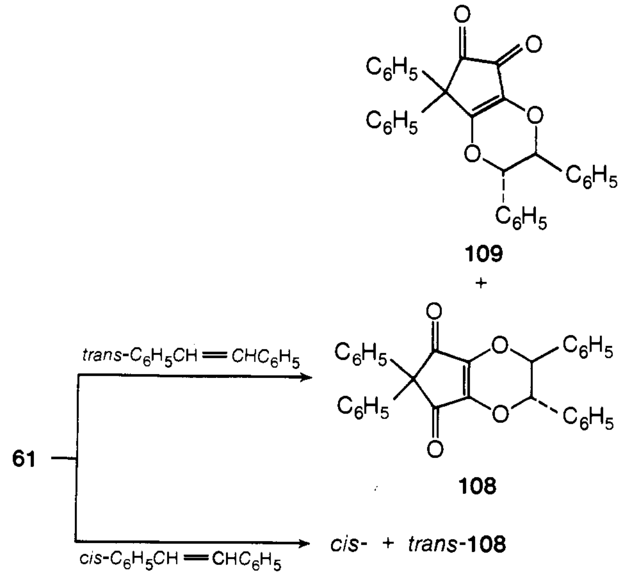
E. Diels-Alder Reactions

The central carbonyl group of the cyclic triones indantrione (**54**), dihydrophenalenetrione (**42**), alloxan (**45**), and quinisatin (**35**) is sufficiently reactive to participate as dienophile in room-temperature Diels-Alder reactions with butadiene and isoprene.[161] Adducts with isoprene could have isomeric structures **106** or **107**; this question was not resolved. Reaction is not restricted to cyclic compounds; diethyl oxomalonate reacted similarly[162] with dienes at elevated temperature.



106 **107**

In contrast to triones, the dihydrate of 5,5-diphenylcyclopentanetetrone (**61**) acted as diene component and formed[95] adducts upon heating with *cis*- or *trans*-stilbene in a manner analogous to the behavior[163] of high potential quinones. The reactions exhibited stereospecificity in one case and regiospecificity in the other; their mechanisms have not been investigated.



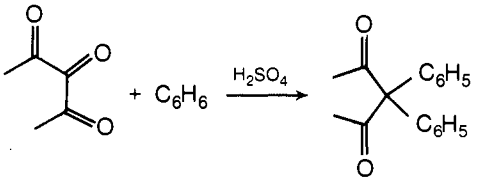
F. Grignard Reactions

Moubasher[164] reported normal Grignard reactions of indantrione (**54**). Using inverse addition of 1 equiv of phenylmagnesium bromide, the expected 2-hydroxy-2-phenylindandione (**110**) was obtained; reaction with excess reagent gave 1,2,3-triphenylindantriol (**111**) probably as a mixture of diastereomers. Both the 2-dimethylketal[165] and the 2-oxime[166] of **54** gave good yields of the product of reaction with 2 equiv of arylmagnesium bromide.

However, reaction of diphenyl triketone with phenylmagnesium bromide did not proceed normally. Kohler and Erikson[167] reported obtaining benzoin benzoate from inverse addition and triphenylcarbinol and benzoin from normal addition. Rearrangement of intermediate magnesium salts was suggested.

G. Friedel-Crafts Reactions

The cyclic triones 1,2-diphenylcyclopentenetrione[95] (**15**), indantrione[164] (**54**), 2*H*,3*H*-dihydrophenalenetrione[168] (**42**), and alloxan[169] (**45**) reacted with benzene in the presence of sulfuric acid to give *gem*-diphenyl products (**112**). Diethyl oxomalonate reacted similarly.[170]

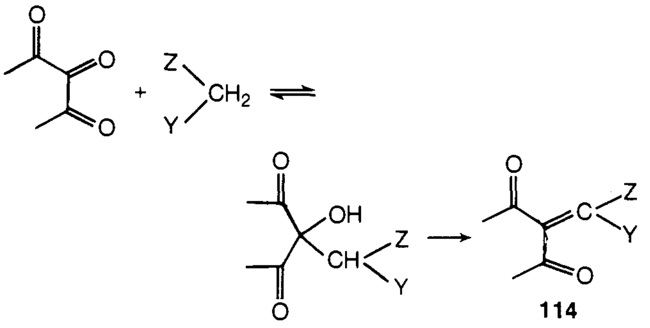


112

The behavior of diphenyl triketone was again different from that of cyclic triones. As noted earlier, with aluminum chloride or sulfuric acid in benzene it gave[157] benzil and other products but no dibenzoylphenylcarbinol or diphenyldibenzoylmethane.

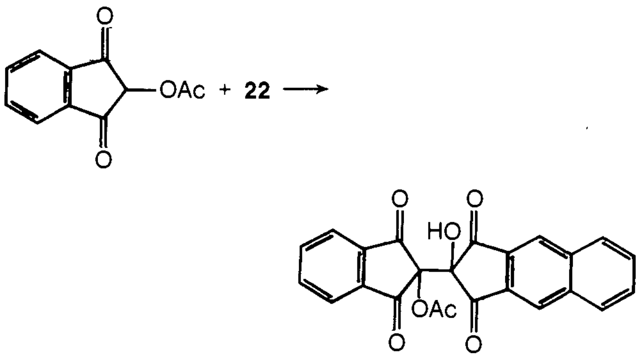
H. Reactions with Active Methylene Compounds

Uncatalyzed reactions of a variety of β-dicarbonyl compounds with indantrione (**54**), 2*H*,3*H*-dihydrophenalenetrione (**42**), alloxan (**45**), and quinisatin (**35**) in dimethoxyethane at room temperature were reported by Schonberg and Singer[171] to give aldols **113** in good yield.



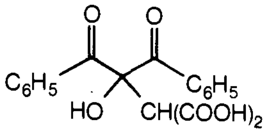
113   **114**

These authors also confirmed the report of Chatterjee[172] that malononitrile and **54** yielded the dehydrated aldol product **114** (Y = Z = CN) directly. No products were obtained with diphenyl triketone. The claim[171] that, with the exception of malononitrile, these reactions require the presence of a carbonyl group in the active methylene compound appears unjustified. Aldol-type products have been obtained by reaction of ninhydrin with nitroethane[173] and of diphenyl triketone, oxomalonic ester, alloxan (**45**) and ethyl β-phenyl-α,β-diketopropionate with α-picoline and quinaldine,[174] and of **42** with ethyl diazoacetate.[185] Uncatalyzed reactions of ninhydrin and its benzo derivative (**22**) with the corresponding 2-acetoxyindandiones have also been reported,[175] *e.g.*

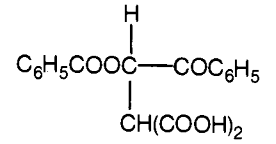


Aliphatic amines have been used as catalysts in a number of condensation reactions. The first such case was recorded by Sachs and Wolff[176] who obtained an unidentified product, $C_{10}H_{10}O_5$ (two molecules of trione minus one of water), when dimethyl triketone was treated with a trace of piperidine; methyl phenyl triketone behaved similarly.[10] Aldol-type products (structures based only on elemental analysis) were obtained from piperidine-catalyzed reactions of dimethyl triketone[176] with malonic acid, acetylacetone and *p*-nitrophenylacetonitrile, of methyl phenyl triketone[13] with acetylacetone, and of methyl o-methoxyphenyl triketone[13] with *p*-nitrophenylacetonitrile. The product of piperidine-catalyzed reaction of oxomalonic ester with cyanoacetic ester was reported[29] to be the dehydrated aldol.

Sharp and Hoffmann[177] obtained 1:1 adducts (by elemental analysis) from reaction of diphenyl triketone with *p*-nitrophenylacetonitrile and with malonic acid (use of sodiomalonic ester led to cleavage of the trione) in pyridine solution containing a trace of piperidine. The malonic acid product, assumed to have the simple aldol structure **115**, did not give isolable product upon attempted dehydration with hot acetic acid, acetic anhydride, phosphorus oxychloride, or sulfuric acid. The alternative structure **116** was suggested since base-catalyzed hydrolysis of the product yielded benzoic acid, glyoxylic acid, and acetophenone; further investigation is indicated.



115

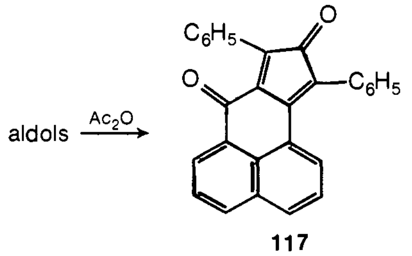


$$C_6H_5COO\overset{\displaystyle H}{\underset{\displaystyle CH(COOH)_2}{C}}-COC_6H_5$$

116

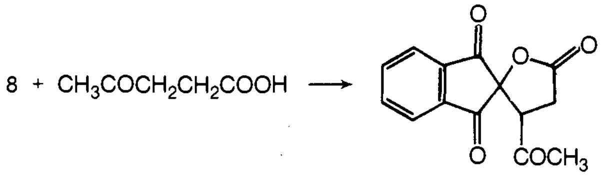
Reaction[85a] of **42** with dibenzyl ketone in the presence of triethylamine afforded a mixture of aldols which was dehydrated to **117**.

$$\mathbf{42} + C_6H_5CH_2COCH_2C_6H_5 \xrightarrow[\text{EtOH, } 50°]{Et_3N}$$



117

As noted earlier, a large variety of compounds react with ninhydrin to give colored products. The lactone **118**, from reaction with levulinic acid, has been characterized.[148]



118

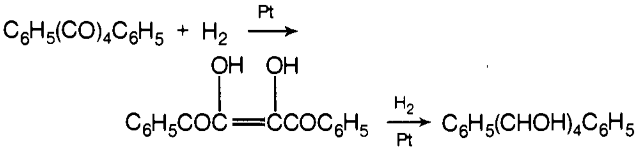
Finally, and most recently, triketones participate in the Wittig reaction to a limited extent. Schonberg, *et al.*,[178] report products from fluorylidenetriphenylphosphoranes with indantrione and dihydrophenalenetrione. Benzylidenetriphenylphosphorane also reacted, but a variety of other phosphoranes appeared to be less reactive to **54** and **42**.

I. Reduction

1. Catalytic Hydrogenation

Reduction of diphenyl triketone[179] or of diphenyl tetraketone[72] over platinum catalyst could be interrupted after uptake of 1 equiv of hydrogen producing dibenzoylcarbinol or dibenzoylformoin, respectively. Further reduction of the latter gave a mixture of diastereomeric tetrols from which five crystalline isomers were isolated.

$$C_6H_5(CO)_3C_6H_5 + H_2 \xrightarrow{Pt} C_6H_5COCHOHCOC_6H_5$$

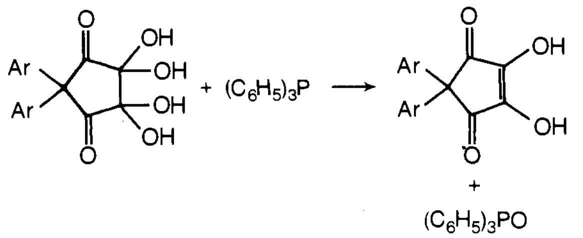


$$C_6H_5(CO)_4C_6H_5 + H_2 \xrightarrow{Pt} C_6H_5CO\overset{OH}{C}{=}\overset{OH}{C}COC_6H_5 \xrightarrow[Pt]{H_2} C_6H_5(CHOH)_4C_6H_5$$

2. Chemical Reduction

The wide variety of reagents which oxidize reductones to polyketones has been summarized in section II.B.2. Polyketones are also readily reduced. Their reduction to reductones by dihydro derivatives of lower polyketones has been mentioned in section VI.D. A number of other reductones, namely triose reductone (dihydropropanetrione), dihydroxymaleic acid, and ascorbic acid have been oxidized[180] to polycarbonyl compounds by 2*H*,3*H*-phenalenetrione (**42**) in aqueous solution. The fate of **42** was not established. Reductions of triones to reductones by sodium borohydride[50,51,59] and hydrogen sulfide[59,67] have been described.

Tetraketones oxidize phenylhydrazine; upon attempted derivatization of dimesityl tetraketone[71] and tetraketotetralin hydrate,[11] the corresponding reductone was obtained. 5,8-Dihydroxytetraketotetralin was reduced[62] by hydrogen sulfide to the dihydro compound. An interesting result is the reduction[95] of 1,1-diarylcyclopentanetetrone dihydrate to reductone by triphenylphosphine with concomitant formation of triphenylphosphine oxide.



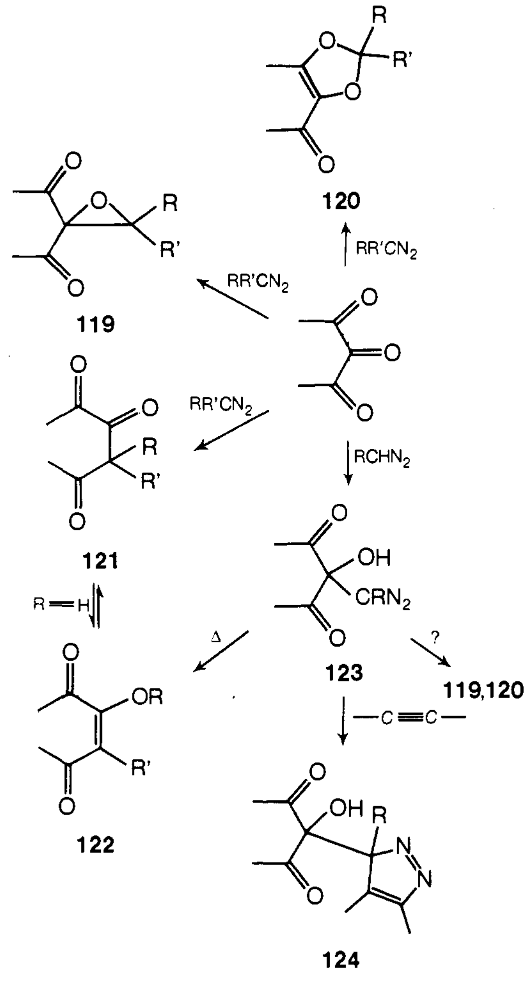
3. Polarographic Reduction

Detailed investigations of the polarographic behavior of indantrione, ninhydrin, and the anion of ninhydrin have been reported by Holleck and coworkers[130,152] and by Kalinowski and Lasia.[181] Ono, *et al.*,[69] investigated dehydroascorbic acid, cyclopentanetrione ("reductic acid"), mesoxaldehyde, and alloxan at pH 3.5. In the aqueous solutions used, the half-wave potentials (relative to normal calomel electrode) were −0.42, −0.7, −0.05 and −0.35 V, respectively. The values observed by Russell and Weiner[182] for diphenyl tri- and tetraketone were −0.76, −2.25 and −0.78, −2.25 V.

J. Reactions with Diazo Compounds

Eistert, *et al.*,[39,183–186] and Schonberg, *et al.*,[187–189] have investigated the reactions of a variety of triones and diazo compounds. As illustrated in Scheme II the possible products include diketo epoxides (**119**), dioxoles (**120**), products of insertion (**121**) which usually exist as the more stable enolic tautomer **122**, and aldol-like products (**123**, isolated when R = COOEt), which rearrange thermally to **122** but can be trapped by acetylenedicarboxylic ester as **124**. Eistert has suggested that **123** may be a common intermediate in these reactions and, in fact, disubstituted diazo compounds, which are incapable of forming **123**, differ in behavior from monosubstituted diazo compounds and from diazomethane. For example, diazomethane, phenyldiazomethane, and ethyl diazoace-

SCHEME II



tate reacted[183] with indantrione by insertion, giving products of ring enlargement, but diphenyldiazomethane and 9-diazofluorene gave[188] epoxides.

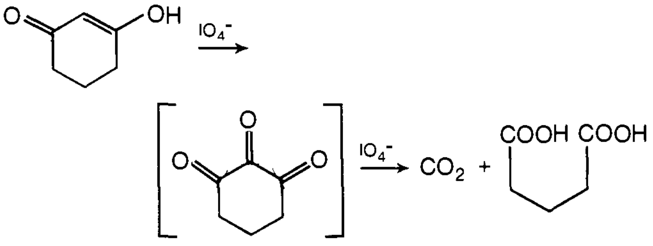
The formation of dioxoles (**120**) appears to be confined[185] to reactions of dihydrophenalenetrione (**42**), which also forms an epoxide (with diazomethane) or upon zinc chloride catalyzed reaction of ethyl diazoacetate. The claim that diphenyl triketone affords a dioxole with diazomethane was shown[186] to be incorrect; the product was the epoxide both with diazomethane and diazoethane. Less reactive diazo compounds gave mainly products of insertion except for 9-diazafluorene which gave epoxide.[188] The results obtained appear to reflect a complex interplay of factors involving both reaction partners.

The hydrate of **42** behaved[185] like the free carbonyl compound. Certain reactions in alcohol solution have yielded pinacols.[189]

K. Miscellaneous Reactions

Reactions of polyketones with trialkyl phosphites have been reported.[190,191] Cyclic enediol esters are obtained[190] from open-chain diaryl triones and simple esters (or the ester of pinacol) from cyclic triones, a result exactly opposite to that observed in reactions of diazo compounds.

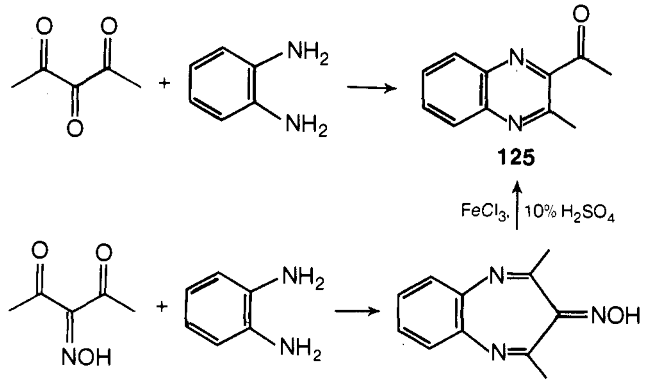
Polyketones give positive tests with oxidizing agents such as Fehling's solution. Oxidation reactions generally lead to products of no particular interest and have been ignored for the most part. An exception is the reported conversion[192] of cyclohexanetrione to glutaric acid using sodium metaperiodate. The authors suggested that oxidation of 1,3-cyclohexanedione to glutaric acid by periodate involved prior conversion to trione.



L. Syntheses of Heterocyclic Compounds

The presence of three or more vicinal carbonyl groups provides opportunity for synthesis of a variety of heterocyclic systems. Some of these have appeared incidental to the preceding discussion; a selection of additional examples follows.

The products which are frequently formed from triketones and o-phenylenediamine have been assumed to have the usual quinoxaline structure. In one case, reaction of the symmetrical oxime of dimethyl triketone with o-phenylenediamine, a seven-membered ring product (**126**) was formed;[193] it underwent hydrolysis and rearrangement to the quinoxaline (**125**) obtained directly from the triketone.[193a,194] The only cases of quinoxaline formation from unsymmetrical triones involve 1-hydroxy-2-phenylcyclopentenetrione and its methyl ether, both of which gave[15] a single product having the structure shown.



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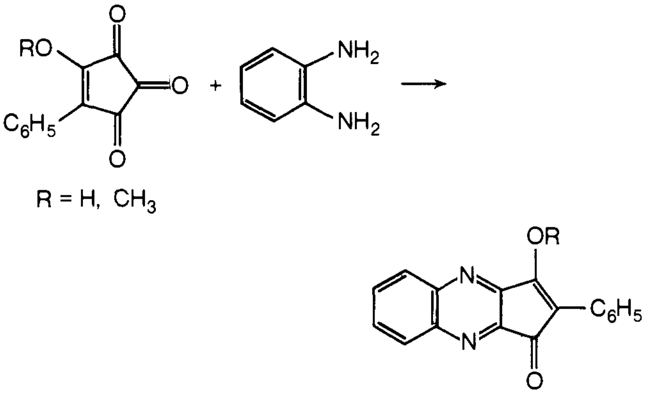
126



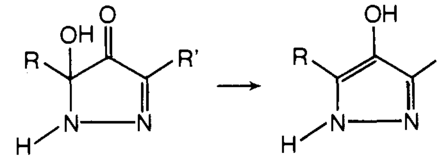
Nye and Tang[195] obtained the hydroxypyrazole **127** (R = R' = C_6H_5) by reaction of diphenyl triketone or its hydrate with hydrazine, thus elucidating the structures assigned by Sachs and Rohmer[10] in 1905 to the products of reaction of hydrazine with dimethyl triketone and methyl phenyl triketone. The later workers also isolated the intermediate **128** from reaction at low temperature. None of the hydrazone **129** was detected.

$R(CO)_3R' \quad + NH_2NH_2 \longrightarrow$

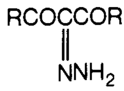
$R = R' = CH_3$

$R = CH_3;\ R' = C_6H_5$

$R = R' = C_6H_5$



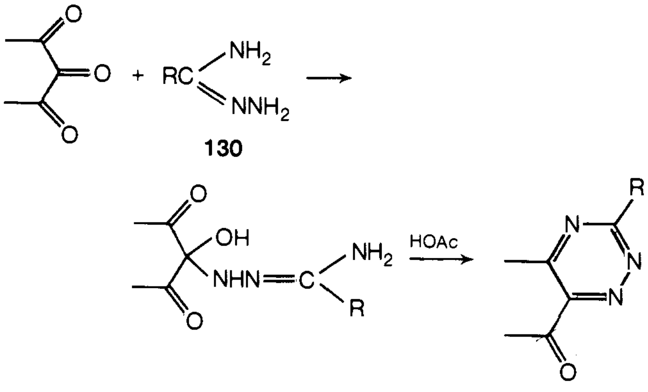
128 **127**



$RCOCCOR'$ with $=NNH_2$ on the central carbon: $RCO\overset{NNH_2}{\overset{\|}{C}}COR'$

129

Ried and Schoman[138] converted the carbinolamines obtained by reaction of aminohydrazones (**130**) with diphe-



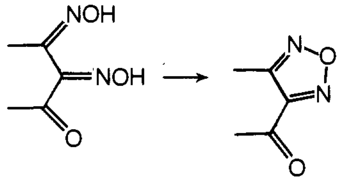
130

131

nyl triketone, ninhydrin, or dihydrophenalenetrione to triazines (**131**) by heating in acetic acid.

Numerous examples of reactions of alloxan which produce heterocycles have been described.[196,197]

Among the reactions of derivatives of triones are formation of furazans (**132**) from α,β-dioximes[108,198,199] phenylazooxazoles (**133**) from oxime hydrazones, and the bis-*N*-oxide (**134**) from 1,3-dioxime.[200]



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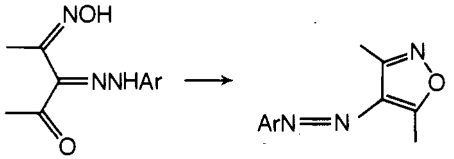

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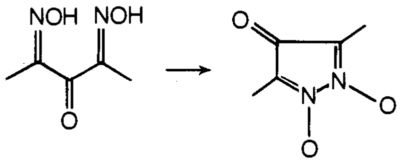

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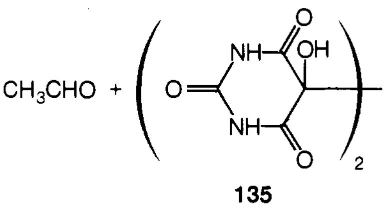
VII. Photochemical Reactions of Polyketones

It is interesting to contrast the intense activity in photochemistry of α-diketones[201,202] with the paucity of results obtained with *vic*-triketones. Quantum yield and triplet energy have been determined[203] for diethyl oxomalonate (E_T = 54 kcal/mol). Beutel[204] has investigated the free-radical-initiated chemiluminescent oxidation of dimedone and suggested that singlet and triplet states of 5,5-dimethylcyclohexanetrione may be responsible for the emissions. The free triplet emitted at ~615 nm with an efficiency of 8×10^{-4} (at maximum oxygen concentration). The triplet energies of most tri- and tetraketones are probably below 45 kcal/mol so that phosphorescence emission cannot be detected with conventional equipment.[31] The reactive excited state has been determined only for the reaction of diethyl oxomalonate with olefins, and no rate data are available for any of the reactions discussed below.

A. Photopinacolization

As with so many aspects of photochemistry, the first photoreaction of a *vic*-trione was reported by Ciamician and Silber.[205] They exposed an ethanol solution of alloxan (**45**) to sunlight and obtained acetaldehyde and the pinacol, alloxantin (**135**). A similar result was obtained[206] in isopropyl alcohol solution. At first glance this reaction would seem to be completely analogous to photopinacolization of ketones such as benzophenone which involves H-atom abstraction by excited ketone (n,π triplet) and dimerization of the resulting ketyl radicals. However, since **45** exists almost completely as the hemiketal in alcohol solution, the mechanistic analogy may not be valid. Recent detailed investigations[207,208] suggest that the pinacol results from dimerization of semitrione radicals (**136**) formed by β-cleavage of the hydrate of hemiketal. The mechanism of formation of the ring-contracted product parabanic acid (**137**) and various cleavage products observed is not clear.

$$45\cdot H_2O + CH_3CH_2OH \xrightarrow{\text{sun}}$$



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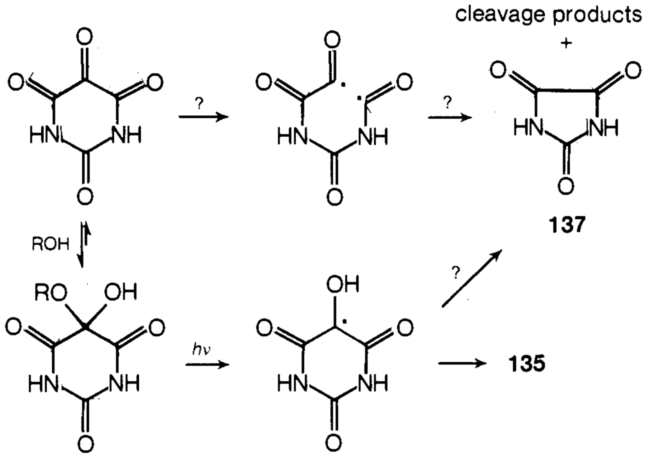

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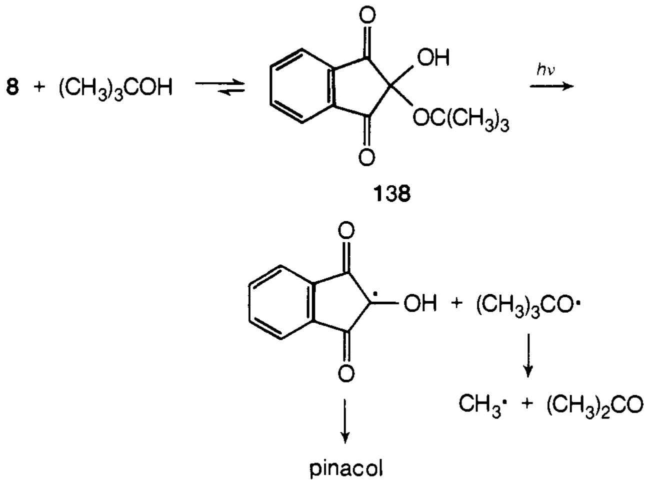
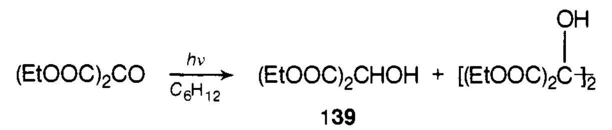
A detailed study[209] of the photopinacolization[210] of ninhydrin (**8**) in alcohol solution showed that a similar mechanism is operative. In particular, irradiation of **8** in *tert*-butyl alcohol solution (the *tert*-butyl hemiketal **138** is an isolable substance), where H-atom abstraction should be very inefficient, afforded the pinacol (hydrindantin) and acetone. These results strongly implicate the *tert*-butoxy radical as an intermediate. Reaction of **8** in aqueous solution gave 58% hydrindantin and 35% of cleavage products (phthalaldehydic acid, phthalic acid, phthalonic acid, phalide-3-carboxylic acid) which might derive from the semitrione radical or be formed *via* α-cleavage. The diethyl ketal of **42** showed similar behavior.[211]



The one pinacol-forming reaction which may involve the usual H-atom abstraction type of mechanism is the irradiation[203] of diethyl oxomalonate in cyclohexane to



$$(EtOOC)_2CO \xrightarrow[C_6H_{12}]{h\nu} (EtOOC)_2CHOH + [(EtOOC)_2\overset{OH}{C}]_2$$

139

give diethyl tartronate (**139**) and its pinacol. The fate of cyclohexane was not determined.

B. Photodecarbonylation

The photochemical conversion of alloxan to parabanic acid has been noted above. Loss of carbon monoxide from *vic*-polyketones might be expected to be a fairly general process as illustrated below. However, the only

$$\mathrm{RCOCOCOR} \xrightarrow{h\nu} \mathrm{R\dot{C}O + RCO\dot{C}O} \longrightarrow$$
$$\mathrm{CO + 2R\dot{C}O} \longrightarrow \mathrm{RCOCOR,\ etc.}$$

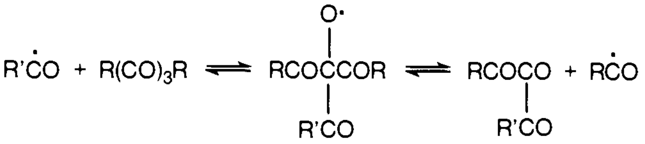
such report (other than alloxan) is a very brief reference by Schonberg and Mustafa[212] to sunlight irradiation of diphenyl triketone which gave benzil. Repetition[31] of this reaction in Haifa sunlight resulted in very slow reaction when careful attention was paid to achieve anhydrous, oxygen-free conditions. In fact, diphenyl triketone in the presence of a variety of reactive substrates was quite inert photochemically provided that careful degassing of solutions was performed. Photoreaction proceeded much more readily in the presence of oxygen. There may be a significant difference of behavior between open-chain and cyclic compounds; degassed tetramethylcyclopentanetrione appears to be converted to tetramethylcyclobutane-1,2-dione.[31]

C. Photoequilibration of Aliphatic Triones

Vapor-phase irradiation[12] of unsymmetrical aliphatic triones or of mixtures of symmetrical triones resulted in scrambling of the alkyl groups to give mixtures of all possible dialkyl triones in addition to traces of diones, carbon monoxide, etc. Similar results were obtained when

$$\left.\begin{array}{c} \mathrm{R(CO)_3R'} \\ \text{or} \\ \mathrm{R(CO)_3R + R'(CO)_3R'} \end{array}\right] \xrightarrow{h\nu} \begin{array}{c} \mathrm{R(CO)_3R + R'(CO)_3R'} \\ + \\ \mathrm{R(CO)_3R'} \end{array}$$

dimethyl triketone was allowed to stand in air with isovaleraldehyde or heated with the aldehyde in the presence of a peroxide. It was suggested that an acyl radical initiated chain reaction is involved as illustrated below:

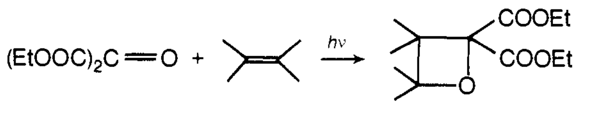


$$\mathrm{R'\dot{C}O + R(CO)_3R} \rightleftharpoons \mathrm{RCO\underset{R'CO}{\overset{O\cdot}{C}}COR} \rightleftharpoons \mathrm{RCO\underset{R'CO}{C}O + R\dot{C}O}$$

Photoinitiation of the chain could be achieved by the α-cleavage illustrated in the section (VII.B) on photodecarbonylation.

D. Cycloaddition with Olefins

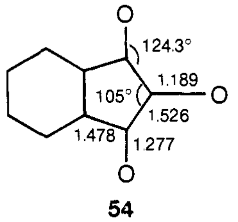
Hara, Odaira, and Tsutsumi,[203] who determined the triplet energy (~54 kcal/mol) of diethyl oxomalonate, also investigated its photochemical reactions at 366 nm with 1,1-diphenylethylene, α-methylstyrene, norbornene, isoprene, and 2,3-dimethylbutadiene. The quantum yield is stated to be 0.3. The reaction leads to formation of oxetanes and appears to be analogous to the well-known Paterno–Buchi reaction of monoketones including regiospecificity in unsymmetrical cases. Good yields of oxetane were obtained except with 2,3-dimethylbutadiene where considerable polymerization of diene was observed.



VIII. Physical Properties of Polyketones

A. Crystal Structure

X-Ray crystallographic analyses of indantrione[213] (**54**), ninhydrin[214] (**8**), alloxan[215] (**45**) and its hydrates[215,216]



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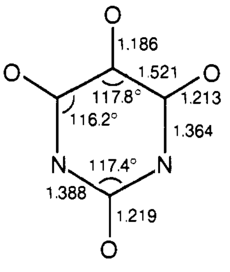
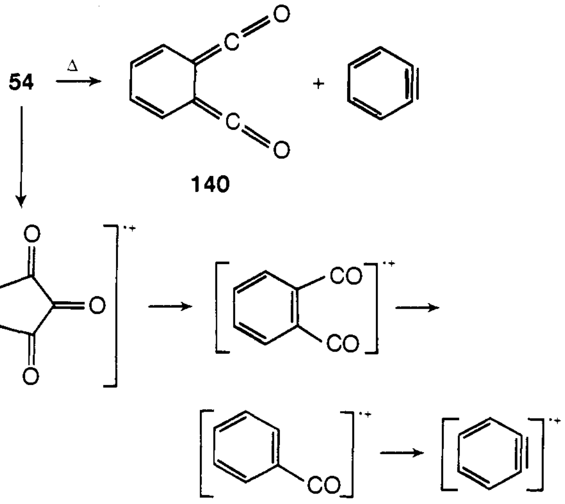


45

have been reported. Both **54** and **8** had planar carbon skeletons. A particular point of interest in **54** was the packing in the crystal; the molecules were arranged in such a way that the carbon atom of the central carbonyl group was in close proximity (2.83 Å) to the oxygen atoms of the carbonyl groups of two other molecules, thus relieving to some degree the unfavorable electrostatic interactions inherent in a cyclic triketone.

B. Mass Spectra

Very little mass spectral data on *vic*-polyketones have been reported. Brown and Solly[217] examined indantrione (**54**) and observed successive eliminations of carbon monoxide as illustrated; the sequential nature of the fragmentation was indicated by appearance of the appropriate metastable peaks. These authors also studied the pyrolysis of **54**: complex mixtures whose composition varied with reaction conditions were observed. The bis-ketene **140** and benzyne were proposed as intermediates which could account for many of the results.



Diphenyl triketone and its hydrate have been examined in Haifa. Again, successive loss of three carbon monoxide molecules was observed for the free triketone. The spectrum of the hydrate showed a very low intensity peak for the hydrate itself. The remainder of the spectrum was identical both in *m*/*e* values and relative intensities with

TABLE I. Absorption Maxima of Tri- and Tetraketones in Methylene Chloride

Compound	λ_{max} (ϵ)
Di-*tert*-butyl triketone	248 (195), 273.5 (70), 283.5 (70), 328 (42), 457 (33),
Diphenyl triketone	sh 254 (12,700), 273 (14,650), sh 290 (9950), sh 350 (175) 450 (45)
Di-*tert*-butyl tetraketone	243.5 (550), 270 (238), sh 288 (205), 386.5 (76), 525 (85)
Diphenyl tetraketone	262.5 (17,700), sh 287 (9840), 385 (160), 515 (200)

that of the triketone suggesting that thermal dehydration occurred in the mass spectrometer.

Investigation[218] of mass spectra of oxocarbons showed a similar pattern of behavior in the series rhodizonic acid (**5**), croconic acid (**4**), squaric acid (**141**). At low source temperature, rhodizonic acid dihydrate gave a parent peak corresponding to dihydrate; a peak corresponding to tetrahydroxy-*p*-benzoquinone was also observed. The spectra of the perhydroxycycloalkanes, octahydroxycyclobutane (**142**), leuconic acid (**6**), and triquinoyl (**7**) were more complex.

C. Ultraviolet–Visible Spectra

Measurement of the absorption spectra of polyketones is complicated by their marked tendency to form hydrates, and many workers have not taken the trouble to determine spectra. Even when spectra have been recorded, the values given for extinction coefficients may be low unless special precautions were taken to use hydrate-free polyketone and rigorously exclude moisture. Horner and Maurer,[30,73] who have made the only detailed studies of ultraviolet-visible spectra of tri- and tetraketones, solved this problem by allowing methylene chloride solutions to stand over phosphorus pentoxide before measurement (0.5–1 hr for triketones, 2–3 hr for tetraketones). The present author has confirmed that reproducible results can be obtained in this way.

The presence of several *vic*-carbonyl groups in a molecule would be expected to lead to absorption maxima arising from a number of n,π^* transitions. These are, in fact, observed as can be seen in Table I (taken from the data of Horner and Maurer). The low intensity maxima in these spectra are attributed to carbonyl n,π^* transitions, and the intense absorptions observed at shorter wavelength in diaryl compounds are undoubtedly due to π,π^* transitions involving the aromatic ring as well. The latter are affected in the expected manner by substitution on the aromatic ring without appreciable effect on the long-wavelength absorption.

These long-wavelength maxima are of particular interest since they vary with structure of polyketone as has also been observed with α-diketones.[219] The data are summarized in Table II. The maxima for all open-chain triketones are at approximately 450 nm. When the three carbonyl groups are constrained in a planar five-membered ring, a large bathochromic shift to above 600 nm is observed (~610 nm for **54** and 685 nm[220] for **79**). In the intermediate case involving a six-membered ring (compound 17a), where puckering of the ring allows a small dihedral angle between adjacent carbonyl groups, an intermediate value of 538 nm is observed. Unfortunately, data are not available on triones having larger rings. These results are reminiscent of the behavior of α-diketones and will be discussed in the following section on conformations of polyketones.

TABLE II. Long-Wavelength Absorption Maxima of *vic*-Polyketones

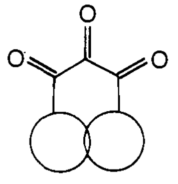
Compound	Solvent	λ_{max} (ϵ)	Ref
Dimethyl triketone	Isooctane (−50°)	~470[a]	11
	CH_2Cl_2[b]	463 (8)	73
Di-*tert*-butyl triketone	CH_2Cl_2[b]	457 (33)	30
4,4,5,5-Tetramethylcyclopentane-1,2,3-trione (**79**)	CCl_4	685 (8.4)	125
Bicyclo[3.2.1]octane-2,3,4-trione (**17a**)	Not given	538	17
Diphenyl triketone	CH_2Cl_2[b]	450 (45)	30
Di-*p*-methoxyphenyl triketone	CH_2Cl_2[b]	440 (89)	30
Di-*p*-nitrophenyl triketone	CH_2Cl_2[b]	457.5 (47)	30
Indantrione (**54**)	Bz	612 (1.46)	132
	CH_2Cl_2[b]	609 (22)	73
	H_2SO^4	549	130
	Dioxane-H_2O	560 (15.5)	128
Dihydrophenalenetrione (**42**)	CH_2Cl_2[b]	557 (25)	73
Di-*tert*-butyl tetraketone	CH_2Cl_2[b]	525 (85)	30
Diphenyl tetraketone	CH_2Cl_2[b]	515 (200)	30
Di-*p*-methoxyphenyl tetraketone	CH_2Cl_2[b]	510 (300)	30
Di-*p*-nitrophenyl tetraketone	CH_2Cl_2[b]	524 (147)	30

[a] Saturated solution. [b] Spectrum determined after standing over phosphorus pentoxide.

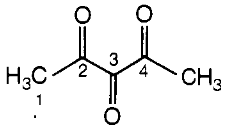
The long-wavelength maxima of open-chain tetraketones are shifted by an additional 75 nm and lie in the range 510–525 nm independent of the end groups present. No spectra of cyclic tetrones have been reported. A collection of tri- and tetraketones provides an attractive spectrum of colors.

D. Conformations of Polyketones

The question of conformation of open-chain triketones, specifically dimethyl triketone, was first discussed by Calvin and Wood[11] in 1940 who pointed out that a planar all s-cis conformation of the triketone is impossible owing to steric repulsion between the methyl groups, a factor which would be even more pronounced with groups larger than methyl. The planar s-trans conformation (preferred for aliphatic α-diketones), which also allows maximal overlap of π orbitals and minimizes unfavorable interactions between adjacent dipoles, was rejected on the basis of unfavorable electrostatic interactions between the oxygen atoms of C-2 and C-4 and because of the small difference between the long-wavelength absorption maxima of biacetyl and dimethyl triketone (*vide infra*). The conclusion was that the three carbonyl groups assume a staggered conformation with dihedral angles between adjacent CO groups, reaching a compromise between resonance stabilization and electrostatic repulsion.



s-cis



s-trans

Horner and Maurer[30,73] have recently considered the problem of conformation of both tri- and tetraketones in detail. Pertinent spectroscopic and dipole moment data are presented in Tables III and IV. The authors based their conclusions in good part on the shifts in long-wave-

TABLE III. Comparison of Long-Wavelength Absorption Maxima of Ketones

	λ_{max} (nm)[a]			
	Monoketone	Diketone	Triketone	Tetraketone
Dimethyl	275	440	463	
Di-*tert*-butyl	295	362	457	525
Diphenyl	337	370	440	510
Dimesityl	342.5	492	471.5	511.5
Cyclopentane[b]		505	685	
Indan		481	606	

[a] In methylene chloride solution. [b] $\alpha,\alpha,\alpha',\alpha'$-Tetramethyl.

TABLE IV. Comparison of Dipole Moments of Ketones[a]

	μ (D)			
	Monoketone	Diketone	Triketone	Tetraketone
Di-*tert*-butyl	2.76	2.55	2.00	2.25
Diphenyl	2.96	3.62	2.45	3.05
Dimesityl	3.05	2.00	2.50	2.40

[a] Data of Horner and Maurer.[30,73]

TABLE V. Carbonyl Maxima in the Infrared Spectra of Polyketones

Compound	λ_{max} (cm^{-1})	Lit.
Di-*tert*-butyl triketone	1695, 1710	30
1,8,8-Trimethylbicyclo[3.2.1]octane-2,3,4-trione	1727	38c
Methyl phenyl triketone	1686, 1727	38c
Diphenyl triketone	1660, 1672, 1709	30
Diphenyl cyclopentenetrione	1688, 1745, 1768	15
Di-*tert*-butyl tetraketone	1690, 1730	73
Di-*p*-methoxyphenyl tetraketone	1661, 1672, 1732	73

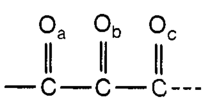
TABLE VI. ^{13}C Chemical Shifts[a] of Ketones in $CDCl_3$

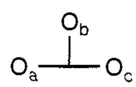
Compound	α-CO	β-CO	C_s	C_o	C_m	C_p
Benzophenone	196.2		137.5	129.8	128.1	132.5
Benzil	194.8		133.2	130.0	129.2	135.0
Diphenyl triketone	192.8	188.5	132.3	130.3	129.2	135.5
Diphenyl tetraketone	188.6	188.0	131.2	130.8	129.3	136.0
Indantrione[b]	183.8	189.1	141.9	137.6	124.9	
Di-*tert*-butyl tetraketone	204.8	188.5	CH_3	25.5	$(CH_3)_3C$	42.5

[a] Ppm relative to tetramethylsilane. [b] In tetrahydrofuran solution.

length absorption maxima in proceeding from mono- to di- and tri- to tetraketones. Leonard and coworkers[221] first showed in 1950, and it has been generally accepted since then, that long-wavelength maxima of α-diketones are shifted by 150–200 nm relative to the corresponding monoketones when the α-dicarbonyl system is coplanar (*cf.* acetone and biacetyl or dimesityl ketone and mesitil) and by much smaller amounts when the dihedral angle between carbonyl groups deviates from 0 or 180° with a minimum at a dihedral angle of about 90°. This generalization appears to be valid for planar triketones as can be seen from the comparison between 3,3,5,5-tetramethylcyclopentanedione (λ_{max} 505 nm) and 4,4,5,5-tetramethylcyclopentanetrione (685 nm) or between indandione (481 nm) and indantrione (606 nm).

If this generalization is applicable to open-chain tri- and tetraketones, it becomes immediately apparent from the data in Table III that these substances do not have coplanar polycarbonyl systems. Horner and Maurer[30] suggested that the dihedral angle between adjacent carbonyl groups in triketones is 90°. If the carbonyl oxygen atoms are labeled a, b, c, then a view along the long axis of the molecule would appear as in **143** and the trione would have a helical structure. It was further proposed that the aryl groups in diaryl triketones are coplanar with the adjacent carbonyl group in order to explain the short-wavelength, intense π,π^* maxima observed. Kroner and Strack[222] in 1972 reported theoretical calculations on dimethyl triketone using a MINDO/2 method and concluded that it has a helical structure (21.8 kcal/mol more stable than the all s-trans conformer). They also proposed that the helix dimensions vary with bulk of alkyl substituent in aliphatic triketones. It might be noted that the dipole moment data are in agreement with a helical structure, among others.





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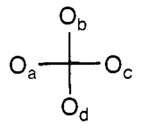
Kroner and Strack also stated that unpublished theoretical work suggested a helical conformation (**144**) for tetraketones. Horner and Maurer, on the other hand, proposed that the two central carbonyl groups of tetraketones assume an s-trans conformation and dihedral angles of 90° with the adjacent terminal CO groups (**145**). The helical conformation has interesting implications.



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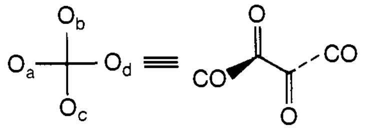

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E. Infrared Spectra

Representative examples of carbonyl maxima in the infrared are presented in Table V. The ubiquitous problem of hydration was encountered here also; some compounds were completely hydrated before spectra could be measured. As can be seen from the table, infrared spectra provide useful information on the types of carbonyl groups present in polyketones.

F. Magnetic Resonance Spectra

Proton magnetic resonance obviously cannot provide direct information on carbonyl groups although it may be quite useful depending on the nature of the groups attached to the ends of a polyketone.

The recent development of pulse Fourier transform methods makes determination of carbon magnetic resonance spectra feasible. Philipsborn and Hollenstein[223] have examined a series of ketones and determined the ^{13}C chemical shifts as summarized in Table VI. The results show a number of interesting trends as the number of vicinal carbonyl groups increases. The resonance of the carbonyl group adjacent to the phenyl ring (α-CO) shifts progressively to lower frequencies while the central carbonyl group (β-CO) is relatively unchanged. The carbon atoms of the attached phenyl groups also show variation in chemical shift, the quaternary carbon atom (C_s) becoming more shielded as the number of carbonyl groups increase while the opposite effect is observed with the para carbon (C_p). Additional carbon spectra will undoubtedly become available in the future and should be very useful.

Electron spin resonance spectra of radical anions derived from ninhydrin[224] and diphenyl triketone[182] have been reported. In the latter case, the semitrione radical anion **146** was obtained with considerable difficulty because of the facile benzilic acid rearrangement of the trione under the basic conditions usually used to generate radical ions. Desired **146** was finally obtained by reaction of trione with the radical anion of benzil since the equilibrium shown below lies far to the right. Reaction of the trione with the sodium salt of thiophenol also gave **146**.

$$(C_6H_5COCOC_6H_5)^{\cdot -} + C_6H_5(CO)_3C_6H_5 \rightleftharpoons \underset{\mathbf{146}}{(C_6H_5(CO)_3C_6H_5)^{\cdot -}} + C_6H_5COCOC_6H_5$$

IX. Tables of Compounds

We have attempted to provide as complete as possible literature coverage of *vic*-polyketones and their derivatives (excepting oxocarbons[5]) through mid-1973 in Tables VII–XV.

The following abbreviations are used for derivatives:

H	hydrazone	Q	quinoxaline
PH	phenyl hydrazone	S	semicarbazone
ArH	aryl hydrazone	K	ketal
Alk	alkazone	hk	hemiketal
Ox	oxime	U	ureide

Position isomerism in derivatives is indicated by a numeral when this is unambiguous or by α, β, γ, . . . , etc.

TABLE VII. Diketoaldehydes, RCOCOCHO

Compound	Trione	Derivatives	Compound	Trione	Derivatives
Mesoxaldehyde (**36**)	Polymer[47–49]	2-PH,[199,225] ArH,[49] 1,3-$(PH)_2$,[101a,b,226,227,229] 1,2-$(PH)_2$,[101,a,b,122,125,227,229] 1,3-$(ArH)_2$,[48,228] Alk,[47,101a,120,122,227,229] 1,3-$(Ox)_2$,[230] $(Ox)_3$,[230] 1,3-$(Ox)_2$-2-PH,[231] K[40]	Pentane-1,2,3-trione		2-PH[232]
			3-Phenylpropane-1,2,3-trione	As intermediate[233]	2-PH[225]
			3-(*p*-Tolyl)propane-1,2,3-trione		2-PH[232]
			3-(*p*-Anisyl)propane-1,2,3-trione		2-PH[232]
Butane-1,2,3-trione		1,2-$(PH)_2$[199,225]	5-Methyl-4-hexene-1,2,3-trione, $(CH_3)_2C{=}CHCOCOCHO$		2-PH[234]

TABLE VIII. Dialkyl Triketones, $R(CO)_3R$

Compound	Ref	Derivatives	Compound	Ref	Derivatives
Dimethyl (pentane-2,3,4-trione)	3, 10–12, 19, 54b, 87	3-PH,[19,100,225,235] $(PH)_2$,[10,19,54b,193b,236] Alk,[193b] 3-ArH,[117,235,237–249] Q,[10,18,19,193a] 3-Ox,[193a,236] 2,3-$(Ox)_2$,[199] 2,3-$(S)_2$,[68,77] OxS,[236] QOx,[193a,b] QPH,[10] OxPH,[199,236] K[245]	Methyl phenoxyoxymethyl		β-PH[250]
			Bis(dialkylaminomethyl)		α,γ-$(PH)_2$[226]
			Methyl β-phenethyl		β-ArH[251]
			Diethyl	12	β-ArH[248]
			Ethyl isobutyl	12	
Dichloromethyl		β-ArH[246]	Di-*n*-propyl		β-ArH[246]
Methyl ethyl	12	α,β-$(PH)_2$,[13] β-ArH,[246] Q,[13] β-Ox[247]	Diisobutyl	12	β-ArH[246]
			Di-*tert*-butyl	30, 295	β-Ox,[295] S,[295] K[295]
Methyl propyl		β-PH[248]	Di-*n*-dodecyl	50	
Methyl isobutyl	12	β-ArH[248]	Dibenzyl		β-ArH[246]
Methyl methoxymethyl		β-PH[249]			

TABLE IX. Alkyl Aryl Triketones, $R(CO)_3Ar$

Compound	Ref	Derivatives	Compound	Ref	Derivatives
Methyl phenyl	Trione,[10,38c,77] hydrate[38c,54b,77]	H,[252] β-PH[10,19,100,225,253] $(PH)_2$,[54] β-ArH,[238,253–258] Q,[10] β-Ox,[259–261] $(Ox)_2$,[259] $(Ox)_3$,[262,263] S,[10,77] OxH[264]	Methyl 4,6-dimethoxybenzofuranyl		β-ArH[266]
			Methyl 4,6,7-trimethoxybenzofuranyl		β-ArH[266]
			Methyl *p*-chlorophenyl		β-Ox[261]
			Methyl 2,4-dichlorophenyl		β-Ox[261]
Methyl *p*-tolyl		β-Ox[261]			
Methyl *o*-methoxy-	13	β-PH,[13] β-ArH,[13] Q,[13] β-Ox,[13] S[13]	Methyl 3,4-dichlorophenyl		β-Ox[261]
Methyl *p*-methoxyphenyl		β-Ox,[261] $(Ox)_3$[263]	Ethyl phenyl		$(Ox)_3$[262]
			tert-Butyl phenyl	30	
Methyl 2,4-diacetoxyphenyl		β-PH[265]	Benzyl phenyl		β-PH,[267] β-Ox[267]
Methyl 2,4-dimethoxyphenyl	13	β-ArH,[13] Q,[13] β-Ox,[13] S[13]	Benzenesulfonylmethyl phenyl		β-Ox[260]

TABLE X. Diaryl Triketones, Ar(CO)$_3$Ar

Compound	Ref	Derivatives
Diphenyl	Trione: 1, 28a, 38c, 42, 43b, 153, 167, 186; hydr: 1, 28a, 38c, 42, 45	β-PH,[1,100,225] β-ArH,[103,246,257,268] H,[195,252], β-Ox,[1,28a,260] α,γ-(Ox)$_2$,[200,269] (Ox)$_3$, K[186,245] anils[1]
Phenyl mesityl	Trione: 20; hydr: 43a	Q[20]
Phenyl p-methoxyphenyl	Hydr: 28a	β-Ox[28a]
Phenyl 3,5-dimethoxyphenyl		β-PH[270]
Phenyl 2-hydroxy-4,6-dimethoxyphenyl	Hydr (?): 88	
Phenyl 2,4,6-trimethoxyphenyl		β-ArH[271]
Phenyl p-chlorophenyl	Trione: 38c; hydr: 38c	
Phenyl o-nitrophenyl		H[252]
Phenyl p-nitrophenyl	Trione: 28a, 38c; hydr: 38c	H,[252] (PH)$_2$,[38c] O[38c]
Phenyl 2-pyridyl	Hydr: 22	β-Ox[22]
Di-p-tolyl	Trione: 30; hydr: 30	
Dimesityl	Trione: 21, 80	β-Ox[21]
Di-p-methoxyphenyl	Trione: 30, 186; hydr: 30	
Di-p-chlorophenyl	Trione: 30, 186; hydr: 30	
Di-p-nitrophenyl	Trione: 30; hydr: 30	β-ArH[103,246]
p-Methoxyphenyl mesityl	Trione; 43c	
Di-β-naphthyl	Trione: 30; hydr: 30	
3,4-Dimethoxyphenyl 2'-hydroxy-4',6'-dimethoxyphenyl	88	

TABLE XI

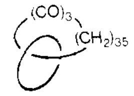
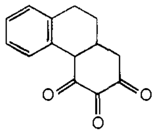
Compound (-trione)	Ref	Derivatives
	A. Monocyclic Aliphatic Triones	
4,4-Difluorocyclobutane-		(Ox)$_3$,[113] (Ox)$_3$, triether[113]
Cyclopentane-1,2,3-	Hydr[66]	1-PH,[272] 1,3-(PH)$_2$,[101b] 1,2-(PH)$_2$,[66] Alk,[66,101b] 1,3-(OX)$_2$[273]
Tetrafluorocyclopentane-1,2,3-		(Ox)$_3$,[113] (Ox)$_3$ triether[113]
4-Methylcyclopentane-1,2,3-		1,2-(PH)$_2$[274]
Tetramethylcyclopentane-1,2,3-	Trione,[125] hydr[59,114,125]	ArH,[125] (ArH)$_2$[125] Q[125] 1,3-(Ox),$_2$[114] (Ox)$_3$,[114] S,[125] K[125]
Cyclopentene-1,2,3-		2-PH,[119] 2-ArH[119]
4,5-Diphenylcyclopentene-1,2,3-	Trione,[15] hydr[15]	Q[15]
4-Phenyl-5-hydroxycyclopentene-1,2,3-	Trione,[15] hydr[15]	Q[15]
4-Phenyl-5-methoxycyclopentene-1,2,3-	Trione[15]	Q[15]
4,5-Dihydroxycyclopentene-1,2,3- (croconic acid)	5	
Cyclohexane-1,2,3-	Hydr[67]	1,3-(PH)$_2$,[67,101b] (PH)$_3$,[67,101b,123,124] 1,3-(Ox)$_2$[105,198]
5-Methylcyclohexane-1,2,3-		Alk,[124] 1,3(Ox)$_2$[105,273]
5,5-Dimethylcyclohexane-1,2,3-	Hydr[22,183]	2-PH[275–276], 2-ArH,[275–277] (PH)$_2$,[183] Alk,[123,124,277] Q$_2$[183] (S)$_2$[183]
5,5-Spiropentamethylenecyclohexane-1,2,3-	Hydr[82]	2-PH,[82] (PH)$_2$,[82] Q[82]
5-Phenylcyclohexane-1,2,3-		2-PH,[278] 2-PH-1,3-(Ox)$_2$[278]
5-(α-Furyl)cyclohexane-1,2,3-		2-PH[278]
4-Carboxycyclohexane-1,2,3-		1,3-(PH)$_2$[67,101b]
5-Carboxycyclohexane-1,2,3-	Hydr[57]	(PH)$_2$,[57] Alk[57]
Xylo-4,5,6-trihydroxycyclohexane-1,2,3-	Hydr[279]	
Cycloheptane-1,2,3-	Hydr[58]	β-ArH,[280,281] (ArH)$_2$,[58] 1,3(PH)$_2$-2-ArH[280]
6-Carbethoxycycloheptane-1,2,3-		2-ArH[280]
Cyclooctane-1,2,3-		2-ArH[281]
Cyclononane-1,2,3-		2-ArH[281]
Cyclodecane-1,2,3-		2-ArH[281]
Cycloundecane-1,2,3-		2-ArH[281]
Cyclododecane-1,2,3-		2-ArH[281]
	B. Polycyclic Aliphatic Triones	
Bicyclo[3.2.1]octane-2,3,4-	Trione,[17] hydr[17]	Q[17]
1,8,8-Trimethylbicyclo[3.2.1]octane-2,3,4-	Trione,[28c] hydr[38c,75]	3-PH,[75,282] 3-ArH,[282] (ArH)$_2$,[75] 3-Ox[75,282]
Bicyclo[3.2.2.]nonane-2,3,4-	Trione,[17] hydr[17]	Q[17]
	Not isolated: 51	
		β-PH[283]

TABLE XII. Cyclic Aromatic Triones

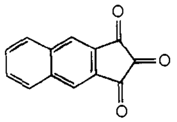
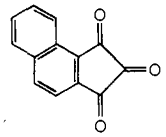
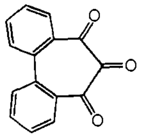
Compound (-trione)	Synthesis	Derivatives
Indan-1,2,3-	Trione[38b,132]	Q,[86] 2-PH,[101b,284,285] 1,2-$(PH)_2$,[86,285] 1,3-$(PH)_2$,[285] $(PH)_3$,[285] 2-ArH,[286] 1,3-$(ArH)_2$,[285] $(ArH)_3$,[285] K[38a,131,209]
5,6-Dimethoxyindan-1,2,3-	Hydr[15b]	
4,5-Methylenedioxy-1,2,3-	?[15b]	
4,5,6,7-Tetrafluoroindan-1,2,3-		2-Ox[27]
	Trione,[24,38b] hydr[24,38b,45]	
	Trione,[24,38b] hydr[24,38b]	
2H,3H-Dihydrophenalene-1,2,3- ("perinaphthindantrione")	Trione,[38c,44,63,86a,b] hydr[38c,44,63,76]	Q,[63] 2-PH,[63,137] 1-PHQ,[63] Ox,[44] hk,[44,63] K,[38c] ureides[135,137]
5-Nitro-2*H*,3*H*-dihydrophenalene-1,2,3-	Trione[64,160b] hydr[64]	Q[64]
6-Nitro-2*H*,3*H*-dihydrophenalene-1,2,3-	Trione,[65] hydr	Q,[65] ureide[65]
6-Bromo-2*H*,3*H*-dihydrophenalene-1,2,3-	Trione[160b]	
	?[25] *cf.* 90	β-ArH,[25,90] $(Ox)_2$[90]

TABLE XIII

Compound (-tetrone)	Lit	Derivatives
	A. Dialkyl Tetraketones, $R(CO)_4R$	
Butane-1,2,3,4-		Alk[120]
Dimethyl		β,γ-$(Ox)_2$,[112,287] $(Ox)_4$[288]
Di-*tert*-butyl	Tetrone[73] Hydr[73]	
Ethyl 2,3,4-triketopentanoate		3-PH[225]
	B. Alkyl Aryl Tetraketones, $R(CO)_4Ar$	
Methyl phenyl		β-Ox[289]
tert-Butyl phenyl	Tetrone,[73] hydr[73]	
	C. Diaryl Tetraketones, $Ar(CO)_4Ar$	
Diphenyl	Tetrone[2,78,94] Hydr[2,72]	$(Q)_2$,[72] $(Ox)_2$[2,78,92,94,290] $(Ox)_4$[288,290]
Di-*p*-tolyl	Hydr[92]	$(Ox)_2$[92]
Di-2,4-dimethylphenyl	Hydr[92]	
Di-2,5-dimethylphenyl	Hydr[91b]	
Di-3,4-dimethylphenyl	Hydr[91b]	
Dimesityl	Tetrone,[71] hydr[71]	
Di-*p*-methoxyphenyl	Tetrone,[73] hydr[73]	
Di-*p*-chlorophenyl	Tetrone,[73] hydr[73]	
Di-*p*-nitrophenyl	Hydr[73]	
Di-α-naphthyl	Tetrone,[73] hydr[73]	
Di-β-naphthyl	Tetrone,[20] hydr[30]	
	D. Cyclic Tetraketones	
Cyclobutanetetrone	5	
5-Methylcyclopentane-1,2,3,4-		2-Ox,[53] 2,3-$(Ox)_2$[53]
5,5-Diphenylcyclopentane-1,2,3,4-	Hydr[95]	
5,5-Di-*p*-tolylcyclopentane-1,2,3,4-	Hydr[95]	$(Q)_2$[95]
5-Cyclohexene-1,2,3,4-		1,3-$(Ox)_2$,[106–109] 1,2,3-$(Ox)_3$,[107,108] $(Ox)_4$,[107] $(OX)_2$-ArH,[108] $(Ox)_2$ $(ArH)_2$[108]
5-Methylcyclohexene-1,2,3,4		1,3-$(Ox)_2$[111,291]
5,6-Dihydroxycyclohexene-1,2,3,4- (rhodizonic acid)	5	
Tetralin-1,2,3,4-	Hydr[11,61,82]	Q,[11,81] 2,3-$(Ox)_2$[11]
5,8-Dihydroxytetralin-1,2,3,4-	Hydr[62,81]	
5,6,8-Trihydroxy-7-ethyltetralin-1,2,3,4- (dehydroechinochrome)	Hydr[62]	

TABLE XIV. Pentaketones

Compound	Ref	Derivatives
Pentane-1,2,3,4,5-		Alk[120]
Cyclopentane-1,2,3,4,5- (leuconic acid)	5	
6-Methylcyclohexane-1,2,3,4,5-		2,4-$(Ox)_2$,[292] $(Ox)_3$[292]
6,6-Dimethylcyclohexane-1,2,3,4,5-		2,4-$(PH)_2$[293]
6-Acetylcyclohexane-1,2,3,4,5-		2,4-$(PH)_2$,[294] 2,4-$(Ox)_2$[294]

TABLE XV. Hexaketones

Compound	Ref	Derivatives
Hexane-1,2,3,4,5,6-		Alk[120]
Cyclohexane-1,2,3,4,5,6- (triquinoyl)	5	
Diphenyl-1,2,3,4,5,6-		2,5-$(Ox)_2$[32]
Di-*m*-tolyl-1,2,3,4,5,6-		2,5-$(Ox)_2$[32]
Di-*p*-methoxyphenyl-1,2,3,4,5,6-		2,5-$(Ox)_2$[32]

X. Appendix

This Appendix, added in proof, includes coverage of the literature through 1974. The order of presentation parallels the original text.

Synthesis

The reaction of α-bromo-β-diketones with DMSO ("Kornblum method", previously applied[44] only for synthesis of **42**) appears to be a good general method for synthesis of triones. It has been used by Berry and Wolfe[296] for synthesis of 1,4-diphenyl-4,4-dimethylbutane-1,2,3-trione **(147)** and by Dahn and coworkers[297] for synthesis of diaryl triones from the corresponding β-diketones (except *p*-nitro-substituted compounds).

The latter workers synthesized a variety of dialkyl, diaryl, and alkyl aryl triones using the N_2O_3 and DMSO–bromo ketone methods for high-yield preparation of diaryl triones and selenium dioxide in dioxane to obtain good yields of dialkyl and aryl alkyl triones. They also found that conversion of α-diazo-β-diketones to triphenylphosphazines followed by reaction with nitrous acid gave very poor yields of triones.

Di-*tert*-butyl triketone has been obtained[295] in low yield by bromination of the α-bromo-β-diketone in the presence of sodium acetate and in even poorer yields by reaction of dipivaloylmethane with nitrosyl chloride. Attempted syntheses[298] of diphenylmethylenecyclobutanetrione *via* selenium dioxide oxidation of the β-diketone or from the α,α-dibromo-β-diketone failed although the dibromo compound was converted to the trione monoketal by reaction with methanol.

Reactions

Uncatalyzed benzilic acid rearrangement of tetramethylcyclohexanetrione **(148)** occurs with unusual facility[299] (presumably *via* the hydrate).

Dahn, *et al.*,[300] have investigated base-catalyzed reactions of a considerable number of open-chain triones and report that, with the exception of diethyl triketone, the major products (66–88%) were not of the benzilic acid rearrangement type **(102)** but instead were carboxylic acids and α-hydroxy acids derived from cleavage between adjacent carbonyl groups. In the unsymmetrical cases studied, cleavage adjacent to the more electronegative or less hindered carbonyl group was favored; this carbonyl group was also favored as the migration terminus. The authors suggest that cleavage involves attack of hydroxide ion at one of the free carbonyl groups of trione hydrate. An alternate possibility is a mechanism analogous to that proposed (*vide infra*) for rearrangement of α-substituted α-hydroxy-β-diketones; the same intermediate **(101)** would be involved both in rearrangement and cleavage. The initial product would then be a pseudo ester which would readily cleave to carboxylic acid and α-keto aldehyde (*cf.* ref 152); disproportionation of the latter to hydroxy acid would complete the process.

Results observed with diphenyl triketone in Grignard reactions and condensations with active methylene compounds have been rationalized. Thus, Kohler and Erikson's[167] observation in 1931 that diphenyl triketone reacts with 1 equiv of phenylmagnesium bromide to give benzoin benzoate and with excess Grignard reagent to give benzoin and triphenylcarbinol represents the first example of base-catalyzed rearrangement of α-substituted α-hydroxy β-diketones to esters of α-hydroxy ketones.[301] This rearrangement, involving a formal carbon-to-oxygen migration of an acyl group, is envisaged as involving attack of the negatively charged oxygen atom in **101** on the adjacent carbonyl group to give an epoxy oxy anion which undergoes carbon–carbon bond cleavage to give the enolate ion of the product. This rearrangement, which requires very dilute base, also accounts for the formation of **116** instead of the expected **115** in the reaction of malonic acid with diphenyl triketone.

Uncatalyzed additions of active methylene compounds, previously reported with cyclic triones in dimethoxyethane, also occur readily[301] with open-chain triketones. The use of piperidine or other amines as catalyst is unnecessary.

Photochemical Reactions

Photolysis of the diethyl ketal of **42** has been reported[302] to involve α-cleavage analogous to the behavior reported previously with alloxan and indantrione derivatives.

Photochemical reactions of diphenyl tetraketone appear[31,303] to be much more efficient than those of diphenyl triketone.

Physical Properties

Berry and Wolfe[296] used variable-temperature proton nmr to study dynamic processes in the aryl alkyl trione **147.** At room temperature **147** exhibited a sharp methyl singlet which broadened enormously on cooling but did not split into two signals even at −140°; similar behavior was observed with α-methyl-α-phenylpropiophenone. It was concluded that the barrier for the process which causes line broadening (interconversion of helical conformers?) cannot be greater than 6 kcal/mol. Heller[31] has succeeded in preparing crystals of diphenyl tri- and tetraketone suitable for X-ray crystallographic analysis. The results of this analysis, which is in progress at the University of Manchester, were not available at the time of completion of this review.

Radical anions of cyclopentanetrione[304] and related compounds[304,305] have been obtained by pulse radiolysis and their esr spectra[304,305a] and polarographic behavior[305b] investigated.

Bischof, Gleiter, and Hofmann[306] have determined photoelectron spectra of tetramethylcyclopentanetrione **(79)**, tetramethylcyclohexanetrione **(148)**, bicyclic triones **17a,b**, and indanetrione **(54)**. The first two ionization potentials were: **79**, IP_1 9.0 and IP_2 10.55; **148**, 9.10 and 10.38; **17a**, 9.49 and 10.60; **17b**, 9.15 and 10.60; **54**, 9.1 and 10.32.

Tables

The following new compounds should be added to the tables: Table VIII, methyl *tert*-butyl triketone^{297} and diisopropyl triketone^{297}; Table IX, 1,4-diphenyl-4,4-dimethylbutane-1,2,3-trione^{296}; Table X, phenyl *p*-tolyl triketone^{297} and di-*p*-tolyl triketone^{297}; Table XIA, 4,4,6,6-tetramethylcyclohexane-1,2,3-trione.^{299}

In addition, new preparations of the following triketones have been reported by Dahn, *et al.*^{297}: dimethyl, diethyl, di-*tert*-butyl (also ref 295), methyl phenyl, diphenyl, phenyl *p*-methoxyphenyl, phenyl *p*-chlorophenyl, phenyl *p*-nitrophenyl, di-*p*-methoxyphenyl, di-*p*-chlorophenyl, and di-*p*-nitrophenyl triketones.

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