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Arenechromium Tricarbonyls in Organic Synthesis

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The characteristic features of the chemical properties of arenechromium tricarbonyls, caused by the change in the reactivity of the aromatic groups and the organic substituents linked to them on passing from ArH to $ArHCr(CO)_3$, are examined and data concerning the application of arenechromium tricarbonyls in organic synthesis are surveyed.
The bibliography includes 167 references.

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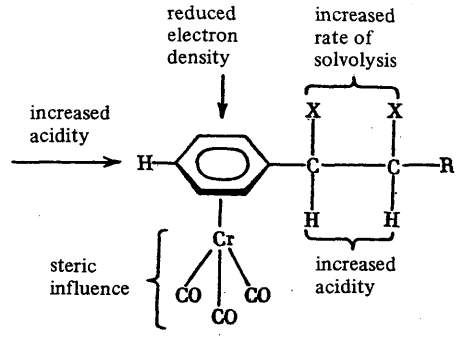
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I. INTRODUCTION

The present stage in the development of organic synthesis is characterised by the wide-scale application of organoelemental and organometallic reagents in order to effect chemoselective, regioselective, and stereoselective processes, which are frequently impossible within the framework of the usual "organic" scheme. During the last 15–20 years, transition metal complexes (TMC) have been vigorously employed in organic synthesis together with traditional derivatives of non-transition metals (Grignard reagents, lithium alkyls), etc.). It is possible to differentiate two main aspects of the application of TMC in synthesis—catalytic reactions and reactions in stoichiometric proportions. The latter presuppose the existence of three stages: (a) the formation of a complex between the organic substrate and the transition metal (TM); (b) the use of the characteristic features introduced by the TM for the chemical modification of the organic residue; (c) decomposition of the complex and isolation of the altered organic molecule. For the effective employment of TMC in synthesis, these stages must proceed with high yields and the complex itself must be cheap and readily available. These requirements are to a large extent satisfied by derivatives of benzenechromiumtricarbonyl (benchrotrene),† which are readily obtained from organic derivatives and $Cr(CO)_6$ or $L_3Cr(CO)_3$ (L = Py, MeCN, or NH_3).

The synthesis of BCT has been examined in detail in various chapters of existing monographs.[1-3] The preparative method has been described specifically in two communications.[4,5] The physicochemical properties of BCT, the nature of the bonding in these compounds, and the principal factors influencing the orientation of the ChTC relative to the arene ligand have been discussed in a review.[6] The reactivity of BCT and their applications in organic synthesis in individual stages have been described in monographs,[7,8] and in greater detail in reviews.[9-14] Striking examples of the employment of BCT in synthesis have been published recently.

The present review deals both with studies having a bearing on specific applications in organic synthesis and studies of the reactivity of BCT which may find applications in the future. The ligand exchange reactions of BCT and the metallotropic rearrangements in a series of condensed systems containing ChTC will not be discussed. Earlier studies included in previous reviews[6,12] are quoted whenever necessary and in a more concise form.



The influence of the formation of a complex with ChTC on the reactivity of the arene ligand.[10]

The formation of a complex between the arene ligand and ChTC imposes characteristic features on the reactivity of the ligand. The changes in the properties of the ligand and the groups linked to it are illustrated in the Figure.[10] The introduction of ChTC leads to strong withdrawal of electron density from the arene ligand (the electron-accepting effect of ChTC is comparable to the influence of the nitro-group),

† The following notation has been adopted in the text of this review: BCT = benchrotrene (PhH)$Cr(CO_3)$ and its ring-substituted derivatives (Arene)$Cr(CO)_3$ also the benchrotrenyl residues $(CO)_3Cr(Ph^-)$; ChTC or [Cr] = $Cr(CO)_3$ group.

which is manifested by the high acidity of the ChTC derivatives of benzoic acids,[15,16] phenols,[17] and anilinium ions[18] compared with the corresponding benzene compounds.

The ability of the aromatic system to transmit the electronic effect of the substituent is significantly reduced in BCT.[16] The correlation of the thermodynamic dissociation constants of 38 substituted ChTC-benzoic acids in 50% aqueous ethanol at 25 °C within the framework of the Yukawa–Tsuno equation showed that the reaction constant ($\rho = 0.8$) is significantly lower than for benzoic acids ($\rho = 1.4$).

The complex formation reaction between the arene and ChTC promotes the stabilisation of α-carbenium ions and to some extent also β-carbenium ions, increases the acidity of the C–H bonds in the arene ligand and in the α-position in an alkyl substituent, and facilitates nucleophilic addition and substitution reactions. ChTC exerts an appreciable steric influence on the reactions of BCT. These effects are used in synthesis.

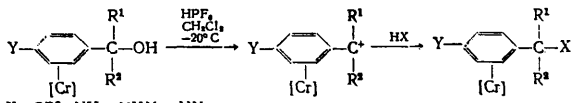
Arenes are usually isolated from BCT by oxidation with iodine[15] or cerium(IV) salts,[19] exposure to light,[20] or displacement with *n*-donor ligands: amines[21] and phosphines.[22]

II. REACTIONS PROCEEDING VIA α-CARBENIUM IONS

A characteristic feature of the BCT substituent, and in general of metallocenyl substituents,[23] is its great ability to stabilise the carbenium centres in the α-position relative to the aromatic ligand. This is indicated by the high rates of solvolysis of $(PhCH_2Cl)ChTC$ and $(Ph_2CHCl)ChTC$ in 80% aqueous acetone, amounting to 2.2×10^{-4} s^{-1} and 7.0×10^{-2} s^{-1}, which is respectively 10^5 and 10^3 times higher than the rate of solvolysis of benzyl chloride and diphenylmethyl chloride.[24] These kinetic results are in good agreement with the thermodynamic stability constants of the carbenium ions:[25] $pK_{R^+} = -11.8$ for $(\pi\text{-}PhCH_2^+)ChTC$. $pK_{R^+} < -17.3$ for $PhCl_2^+$, and $pK_{R^+} = -13.4$ for Ph_2CH^+.

The formation of complexes with ChTC appreciably increases the rate of isomerisation of benzyl thiocyanate to benzyl isothiocyanate [$(PhCH_2SCN)ChTC \rightarrow (PhCH_2NCS)ChTC$];[26] the rate-determining stage of the process is ionisation.

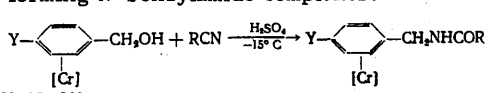
The formation of complexes by benzyl alcohols with ChTC and the subsequent generation of carbenium ions lead to extensive possibilities for the synthesis of *N*- and *O*-benzyl derivatives. The reactions of ChTC-containing carbenium ions with NH_3, amines, and alcohols provide convenient methods of synthesis of the corresponding derivatives:[27]



X=OR³, NH₂, NHMe, NMe₂
Y=H, OMe
R¹, R²=H, Me, Ph
R³=Me, Et

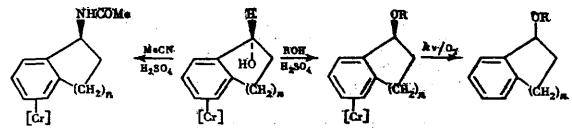
This approach greatly expanded the range of alcohols used in the Ritter reaction. Tertiary alcohols usually afford satisfactory yields of amides in this reaction, while the use of primary and secondary alcohols leads to unsatisfactory results.

The primary BCT-carbinols react smoothly with various nitriles, forming *N*-benzylamide complexes:[28,29]



Y=H, OMe
R=Me, Pr, Ph, *o*-MeC₆H₄, PhCH₂, ClCH₂, CH₂=CH

The formation of complexes with ChTC imparts characteristic features to the stereochemical course of the reactions of the intermediate carbenium ions. This is clearly illustrated by the total stereospecificity of the reactions of the carbenium ions generated from (*endo*-1-indanol)ChTC (I) and (*endo*-1-tetralinol)ChTC (II): the reactions with H_2O, MeOH, and RCN are accompanied by the complete inversion of configuration and the formation of *exo*-products:[29–31]

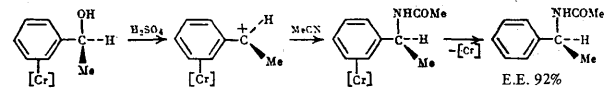


(I), (II)

R=H, Me; n=1 (I), 2 (II)

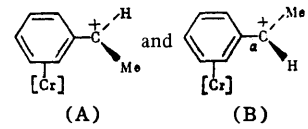
The racemisation of optically active complexes is not observed in these reactions and the photochemical decomposition of the complexes also proceeds with almost 100% retention of configuration.

Even in the acyclic series the reaction of BCT-carbinols via carbenium ions proceeds with an appreciably stereoselectivity.[29,32] The high degree of retention of optical purity in the products formed has been demonstrated in relation to the reactions of optically active *S*-(+)-(α-hydroxyethylbenzene)-ChTC, for example:



E.E. = enantiomeric excess.

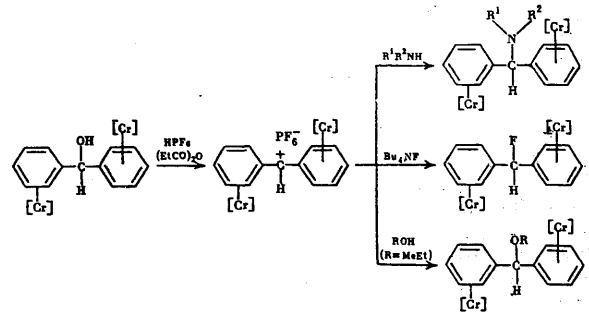
The retention of configuration in acyclic systems can be explained by *exo*-attack in the formation of the carbenium ion and in its subsequent reactions, i.e. of the two potentially feasible carbenium ions (A) and (B), namely



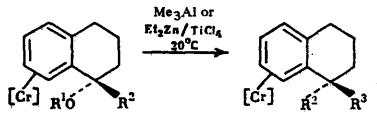
(A) (B)

the ion (A) is formed and the interconversions (A) ⇌ (B) are hindered by the high energy barrier to the rotation about the C(1)–C(α) bond.[33]

The stable α-carbenium ions with two ChTC, isolated in the solid crystalline state, are of special interest.[34,35] They are formed in the reaction of doubly complexed diphenylmethanol in propionic anhydride with 55% HPF_6. On treatment with alcohols, these complexes give rise to esters, while their reactions with primary and secondary amines afford secondary and tertiary amines respectively. Reactive aromatic substrates, namely dimethylaniline, pyrrole, and *N*-methylpyrrole are alkylated by carbenium ions but anisole and less nucleophilic aromatic derivatives do not react with them.[34,45] The reaction with tetrabutylammonium fluoride yielded the corresponding π-complex of diphenylmethyl fluoride:[27]

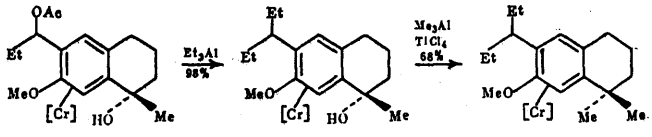


The ChTC-derivatives of *endo*-benzyl alcohols and their acetates are convenient sources of alkyl derivatives, which are obtained by reaction with Me_3Al or Et_2Zn in the presence of $TiCl_4$:[36]

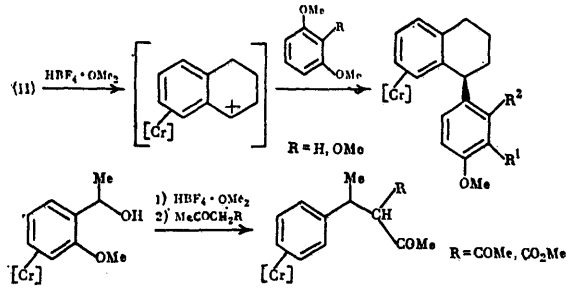


R^1 = H, Ac; R^2 = H, Me; R^3 = Me, Et

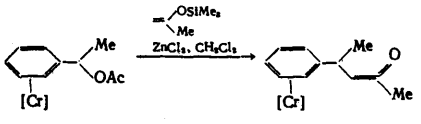
Depending on the conditions, when the substrate contains two types of benzyl hydroxy-groups, it is possible to introduce stepwise different alkyl groups:



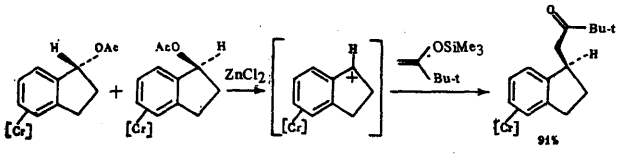
The BCT-carbenium ion, formed *in situ*, reacts rapidly with aromatic derivatives containing electron-donating groups and with β-dicarbonyl compounds, forming *exo*-substituted complexes:[37]



The acetates of α-BCT-carbinols are active alkylating agents and produce ketones smoothly in reactions with silyl enol ethers,[38] for example:



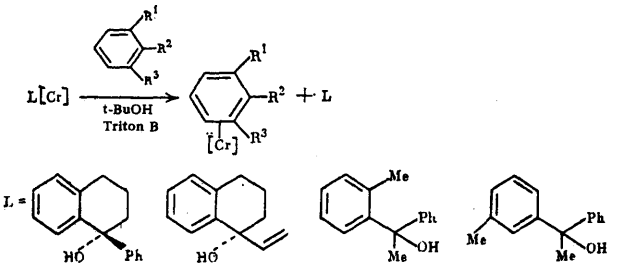
The reaction of a distereoisomeric mixture of indanyl acetates, bound in a complex, with 1-t-butyl-1-trimethylsiloxyethylene leads to a single *exo*-substituted complex via an intermediate carbonium ion with planar chirality:



The alkylation of enol ethers by the acetates of α-BCT-carbinols provides a convenient preparative method for the stereospecific formation of a C–C bond.

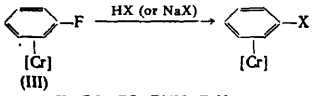
It is noteworthy that it has been suggested that BCT with t-hydroxy-groups in the ligand, which exhibit an increased tendency towards the formation of carbenium ions, be employed for the transfer of ChTC to other arenes.[39,40]

The reaction is used for the synthesis of BCT with functional-group substituents:



III. NUCLEOPHILIC SUBSTITUTION AND ADDITION

The strong electron-accepting effect of ChTC facilitates reactions involving nucleophilic substitution in (η^6-halogenoarene)ChTC. The fluorine and chlorine atoms in BCT are readily substituted by *O*-, *S*-, and *N*-nucleophiles, the fluorobenzene complex (III) exhibiting the highest reactivity:[41–44,75]



(III)

X=RO, RS, RNH, R_2N

The relative ease of substitution of the halogen by the MeO group in halogenobenzenes activated by complex formation increases in the following sequence for different π-linked organometallic residues:[45,46]

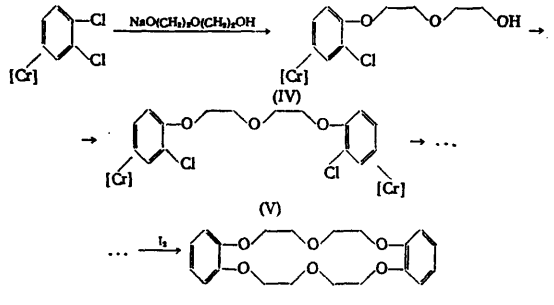
$$(OC)_3Cr < (OC)_3Mo < (\eta^5\text{-}C_5H_5)Fe^+ < (OC)_3Mn^+$$

Difluoro-BCT readily exchanges both fluorine atoms for methoxy-groups.[47]

The halogen in (halogenbenzene)ChTC is readily exchanged for the mercapto-group under the condition of phase-transfer catalysis.[48]

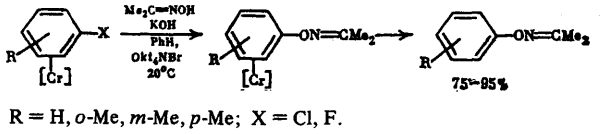
In (dichlorobenzene)ChTC, the substitution of the halogens can be carried out consecutively.[49,50]

The possibility of the stepwise substitution of chlorine atoms in (1,2-dichlorobenzene)ChTC permitted its use in the synthesis of dibenzo-18-crown-6 ether by reaction with the sodium salt of diethylene glycol via the complexes (IV) and (V):[51]



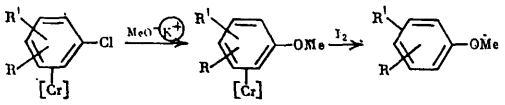
The yield of the crown ether is 27%.

Under the conditions of phase-transfer catalysis, BCT reacts smoothly with acetone oxime, forming *O*-aryloximes:[52]



R = H, *o*-Me, *m*-Me, *p*-Me; X = Cl, F.

When (chloroarene)ChTC is heated with non-solvated MeOK in benzene or acetonitrile in the presence of 18-crown-6 ether, (methoxyarene)TC is formed in high yields:[53]



R, R' = H, Me, OMe, NMe_2
(K^+) = K^+/18-crown-6 ether

Intramolecular nucleophilic substitution in the series of BCT is an effective method of synthesis of benzocyclic systems, for example, chromans:[54,55]

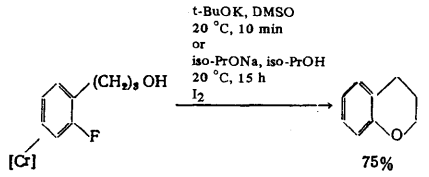
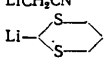
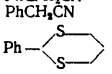
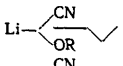
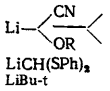
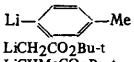
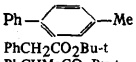
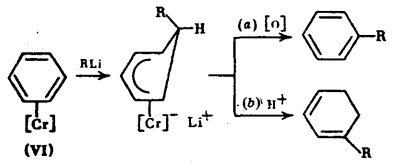


Table 1. The coupling of carbanions to BCT [Eqn.(1a)].[10,56]

Carbanion	Product	Yield, %
$LiCMe_2CN$	$PhCMe_2CN$	94
$LiCH_2CN$	$PhCH_2CN$	68
		93
	$PhCO(CH_2)_2Me$	90*
	PhCOPr-iso	88*
$LiCH(SPh)_2$	$PhCH(SPh)_2$	84
LiBu-t	PhBu-t	97
		71
$LiCH_2CO_2Bu$-t	$PhCH_2CO_2Bu$-t	87
$LiCHMeCO_2Bu$-t	$PhCHMeCO_2Bu$-t	88
$LiCMe_2CO_2Bu$-t	$PhCMe_2CO_2Bu$-t	88

*R = CHMeOEt; the products were isolated by successive acid and base hydrolysis.

A notable property of *C*-nucleophiles is their ability to add to BCT with formation of η^5-cyclohexadienyl complexes, which are formal analogues of Meisenheimer complexes.[56] The reaction takes place rapidly at 0 °C. It has been shown from the products of the addition of the lithiodithiane complex to BCT that the entering substituent occupies the *exo*-position in the structure, where one of the ring carbon atoms is deflected in the opposite direction relative to ChTC.[57] Anionic complexes are capable of two types of reactions:

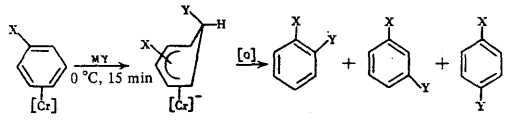


(1)

The oxidation of the complex leads to the formal substitution of the hydride ion by the carbanion (pathway *a*) and the formation of a substituted benzene. The process has come to be called "addition/oxidation".[56,58] The protonation of the complex by strong acid liberates alkylcyclohexa-1,3-diene ("addition/protonation", pathway *b*).[56,59,60] "Addition/oxidation" has potentially many applications in organic synthesis for the phenylation of organic compounds (Table 1).[10,56]

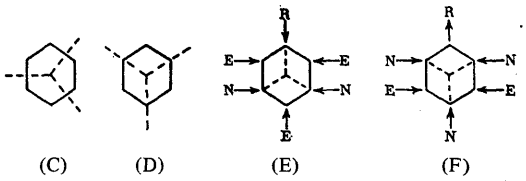
Reactive organolithium compounds are effectively phenylated by BCT under mild conditions in tetrahydrofuran (THF).

Table 2. The mode of addition of carbanions to BCT.[61,62]



X	MY	Product ratios *o*:*m*:*p*
Me	$LiCH_2CO_2Bu$-t	28:72:0
Me	$LiCMe_2CO_2Bu$-t	3:97:0
Me	$LiCMe_2CN$	1:97:2
Me		51:47:2
OMe	$LiCH_2CO_2Bu$-t	4:96:0
Cl	$LiCH_2CO_2Bu$-t	54:45:1
Cl	$LiCHMeCO_2Bu$-t	53:46:1
Cl	$LiCMe_2CO_2Bu$-t	5:95:1
Cl	$LiCH_2COBu$-t	76:24:0
Cl	$LiCMe_2CN$	10:89:1
Cl		46:53:1
$SiMe_3$	$LiCMe_2CN$	0:2:98
CF_3	LiC(CN)(OR)Me	0:30:70
NMe_2	$LiCMe_2CN$	1:99:0
Et	LiC(CN)(OR)Me	0:94:6
iso-Pr	LiC(CN)(OR)Me	0:80:20
t-Bu	LiC(CN)(OR)Me	0:35:65
$CH(Bu\text{-}t)_2$	LiC(CN)(OR)Me	0:0:100

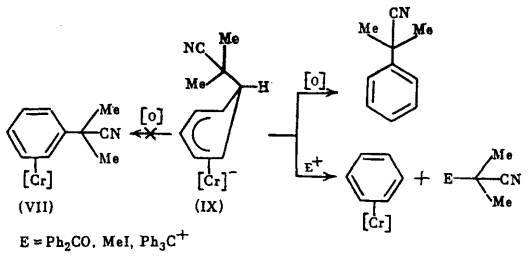
In substituted BCT the nature of the substituent has a decisive influence on the regioselectivity of the addition of nucleophiles (Table 2).[61,62] To a lesser extent the ratio of the isomers is influenced by the nature of the nucleophiles. The direction of attack by the reactants on BCT is qualitatively correlated with the coefficients of the lowest unoccupied molecular orbital of the free arene, which is associated with the distribution of charge density, and attack by the nucleophiles Nu is directed preferentially to the carbon atom eclipsed by the CO group, while that of the electrophile E is directed to neighbouring atoms.[63-66] Despite the low energy barrier between the hindered (C) and eclipsed (D) conformations (~0.3 kcal mol^{-1}), BCT's with an electron-donating substituent exist preferentially in the *syn*-eclipsed conformation (E), while those with an electron-accepting substituent exist in the *anti*-eclipsed conformation (F):



(C) (D) (E) (F)

Nucleophilic substitution takes place in the *m*-position in complexes with R = OMe or NMe_2 and in the *p*-position in those with R = CF_3 or $SiMe_3$. Alkyl-BCT are an exception.[67] With increase of the bulk of the alkyl group, *p*-attack become

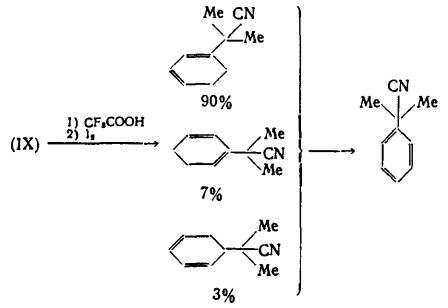
preferred to *m*-attack. The attempts to obtain the complex (VII) by the selective oxidation of the adduct (IX), obtained by the reaction of the BCT with 2-lithio-2-methylpropionitrile (VIII) on treatment with I_2, $FeCl_3$, benzoquinone, $CuCl_2$/DMF,# and cerium(IV), led only to the formation of 2-methyl-2-phenylpropionitrile. When electrophiles are used as hydride ion acceptors, the initial arene complex is regenerated as a consequence of the abstraction of the carbanion: [56,57]



(VII) (IX)

E = Ph_2CO, MeI, Ph_3C^+

The intermediate (IX) reacts rapidly with proton donors (H_2O, AcOH, CF_3CH_2OH) to regenerate the initial BCT in 70–90% yield, while on treatment with CF_3COOH (5 equiv.) and subsequent oxidation a mixture of isomeric cyclohexadienes is formed and can be readily aromatised: [57]

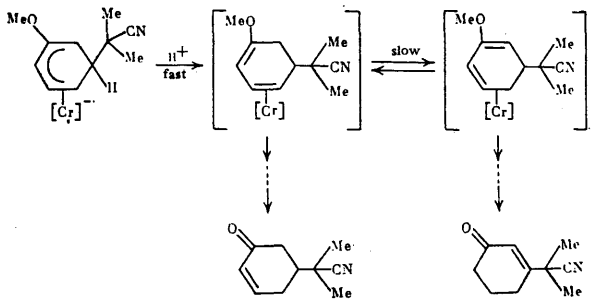


90%

7%

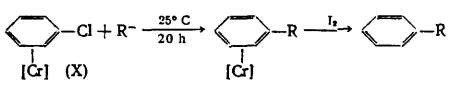
3%

In the case of the adduct of (η^6-anisole)ChTC and compound (VIII), proton transfer results in the formation of dienol ethers, whose hydrolysis affords 3- and 5-substituted cyclohexenones; the ratio of the latter depends on the duration of stirring with acid:



If the adducts of nucleophiles with BCT are treated with CF_3COOH in an atmosphere of CO, then $Cr(CO)_6$ is readily regenerated together with dienes or arenes. [68]

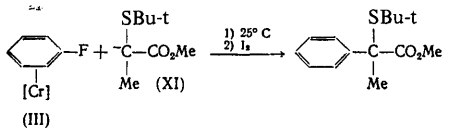
The reaction involving nucleophilic substitution of chlorine in (η^6-chlorobenzene)ChTC by stabilised carbanions, which can be regarded as a preparative phenylation method, has been discovered: [69,70]



R=CMe_2CN, CMe_2CO_2Et, $CMe_2CO_2^-$, $CH(CO_2Et)_2$, C(Ph)(CN)(OCHMeOEt)

The lithio-derivatives of 1,3-dithiane, 2-methyl-1,3-dithiane, t-butyl acetate, acetophenone, 5,6-dihydro-2,4,4,6-tetramethyl-4*H*-1,3-oxazine, and acetonitrile are not phenylated under these conditions. Primary and secondary carbanions are apparently relatively ineffective in this reaction owing to the presence of an active hydrogen atom. The diethylmalonate anion, which reacts slowly with the complex (X), is an exception.

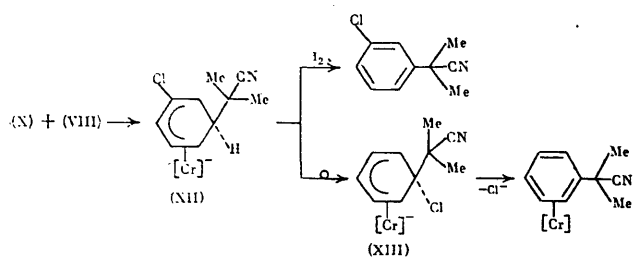
It has been shown that the fluorine-containing complex (III) reacts rapidly with the carbanion (XI), giving rise to methyl α-(t-butylthio)-α-phenylpropionate in 94% yield after the decomposition of the complex:



(III)

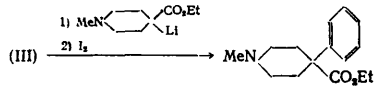
The rate of nucleophilic substitution of the halogen in (η^6-halogenobenzene)ChTC depends on the character of the leaving group and diminishes in the sequence F > Cl > I. [70]

The mechanism of the nucleophilic substitution of the halogen in halogeno-BCT is complex. For example, when (chlorobenzene)ChTC (X) is treated with 2-lithio-2-methylproprionitrile (VIII) at −78 °C and is then oxidised, a 1,3-disubstituted benzene is formed. However, at 20 °C the intermediate (XII) slowly isomerises to the complex (XIII), which loses Cl^- and gives rise to an *unco*-substitution product: [56]

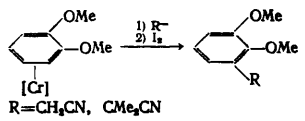


(XII) (XIII)

Nucleophilic substitution and addition reactions have found applications in fine organic synthesis. Thus substitution of the fluorine atom in (PhF)ChTC (III) by the carbanion derived from 4-ethoxycarbonyl-1-methylpiperidine leads to the analgesic demirol in 85% yield: [56]

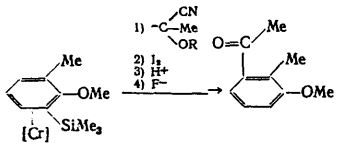


The regioselectivity of the nucleophilic attack has been used in the synthesis of polysubstituted benzenes. The role of the MeO and Me_3Si groups as *m*- and *p*-directing groups respectively is a decisive factor in the synthesis of 1,2,3- and 1,2,4-trisubstituted benzenes: [62]

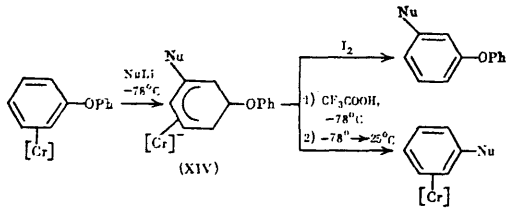


R=CH_2CN, CMe_2CN

DMF = dimethylformamide.

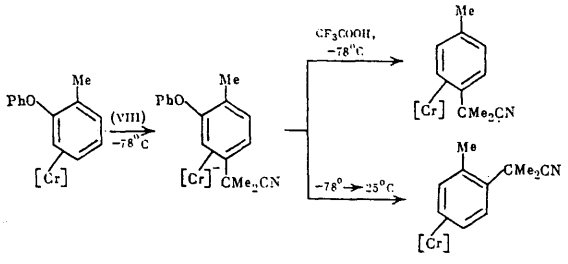


It has been shown[71] that (diphenylether)ChTC reacts with stabilised carbanions to form *m*-substituted diphenyl ethers after oxidation. If the anionic complex (XIV) is treated with CF_3COOH at −78 °C or is heated to room temperature, then the product of the substitution of the PhO group by the nucleophile is formed:

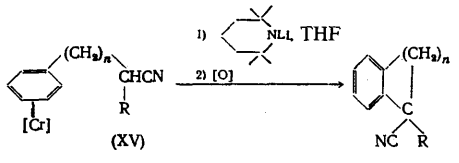


Nu = CH_2CN, CHMeCN, CMe_2CN, $CHMeCO_2Bu$-t, C(Ph)—S—$(CH_2)_3$—S

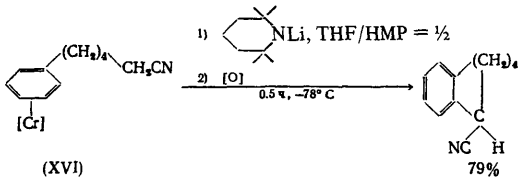
The high regioselectivity of the substitution of the phenoxy-group has been established for the reaction of (*o*-phenoxy-toluene)ChTC with compound (VIII): treatment with CF_3COOH leads to a p-disubstituted complex, while heating to room temperature affords the *o*-disubstituted complex:



The nature of the product formed has been investigated as a function of the number of methylene units separating the aromatic ligand and the CN group for systems capable of intramolecular addition.[72] 1-Cyanotetralin is formed from the complex (XV, $n = 3$);

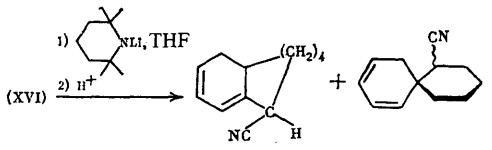


When $n = 4$, the position where the nucleophile adds depends on the reaction time and temperature:

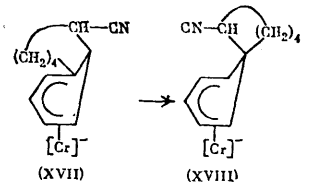


With increase of temperature and of the reaction time, the fraction of high-molecular-weight products also increases.

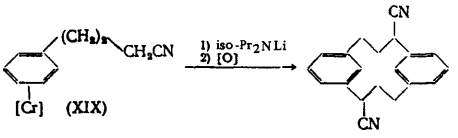
High yields of monomeric products are retained under protonation conditions, but their ratio also depends on the reaction time and temperature. For example, the amounts of condensed and spiro-products at 0 °C are 25 and 75% after 4 h and 3 and 97% respectively after 24 h:



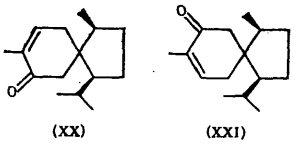
The most rational explanation involves the initial formation of compound (XVII) as the kinetically controlling product; a 1,2-carbon shift converts this adduct into the thermodynamically more favourable complex (XVIII):



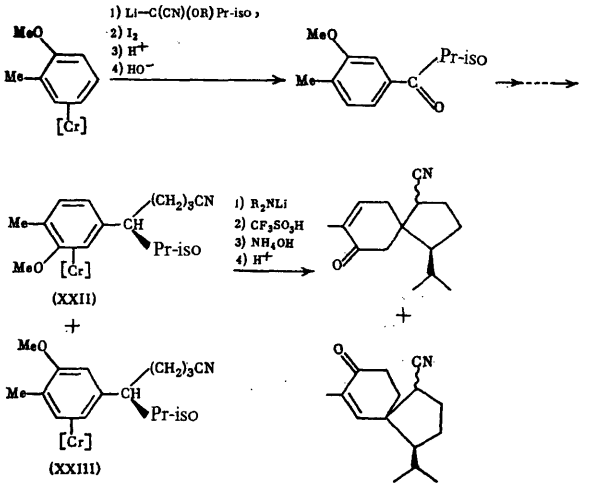
For low homologues (XIX, $n = 2$), the formation of both spirocyclic and condensed products is favourable, so that dimeric compounds are formed:



The characteristic features of the addition of nucleophiles have been used in the synthesis of spiro[4.5]decane system—acorenone (XX) and acorenone B (XXI):[14]

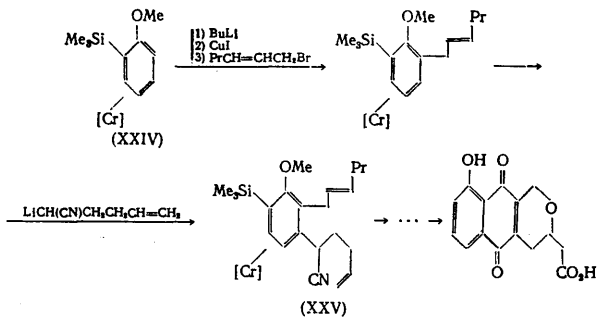


The strategy used in the synthesis is based on the *m*-directing effect of the methoxy-group in the nucleophilic addition to the anisole complex; *exo*-attack is then controlled by the configuration of the spiro-carbon:



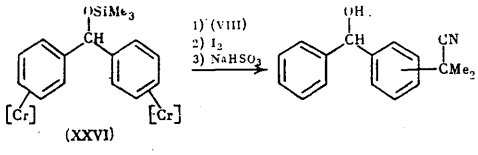
The diastereoisomeric mixture of the complexes (XXII) and (XXIII) was separated by preparative liquid chromatography; the low efficiency of the spirocyclisation complexes vitiates the prepartive importance of this synthesis.

Complex formation with ChTC has been a convenient method of preparation of synthons on the way from frenolicin to deoxyfrenolicin—antibiotics based on the isochromanquinone skeleton.[74] The fundamental factor is the use in the initial stages of the *p*-directing effect of the Me_3Si group and the *m*-directing effect of the MeO group in the nucleophilic addition of the complex (XXIV); this results in the selective formation of compound (XXV), from which the Me_3Si group can be readily removed. It is noteworthy that the lithio-derivative of the complex (XXIV) does not react directly with 2-hexenyl bromide and was therefore converted into an organocopper derivative:

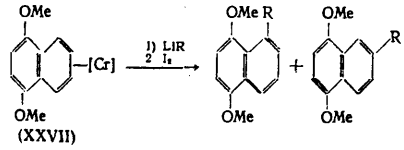


The overall yield of deoxyfrenolicin is 4% after a 15-stage synthesis.

The decisive role of the conformation of ChTC in the mode of nucleophilic attack on the BCT has been confirmed.[75] The reaction of 2-lithio-2-methylpropionitrile with the complex (XXVI), for which the *syn*-eclipsed conformation is characteristic, and subsequent oxidation yielded a mixture of mono-substituted diphenylmethanols with the ratio *m*/*p* = 9/1:

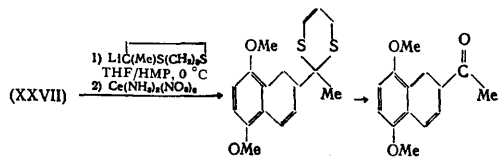


The addition of nucleophiles to polycyclic aromatic complexes is of considerable interest. In this case the steric requirements of the arene substituent and the nucleophile have a marked influence on the regioselectivity of the nucleophilic attack together with the conformational effect and the nature of the substituent in the nucleus.[76] The reaction of the small $LiCH_2CN$ molecule with the complex (XXVII) affords mainly the α-substitution product, while the more bulky compound (VIII) gives rise to the β-substitution product:

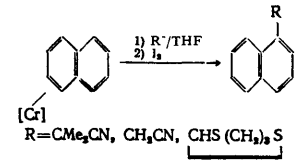


Depending on the reaction time and temperature, different ratios of the α- and β-products are observed and the β-addition product rearranges via dissociation with elimination of a carbanion to the thermodynamically favourable α-addition product.

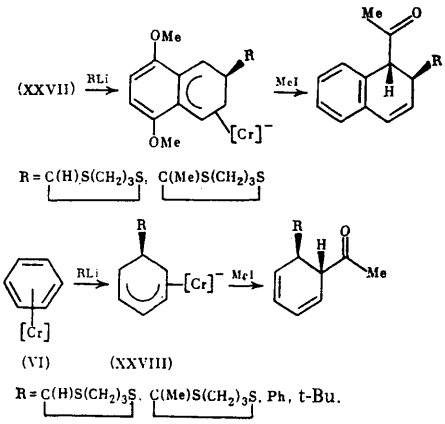
In the case of 2-lithio-2-methyl-1,3-dithiane, the β-addition is irreversible and this reaction has been used to synthesise 6-acetyl-1,4-dimethoxy-5,6-dihydronaphthalene—the synthon in the synthesis of daunomycin:



However, carbanions add to (naphthalene)ChTC in the α-position:

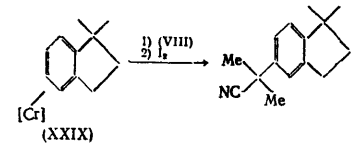


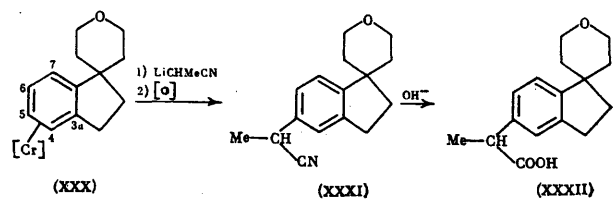
The ability of *S*-stabilised carbanions to add irreversibly to BCT with formation of anionic complexes, which react with electrophiles (MeI), is the basis of a general method of synthesis of disubstituted dihydronaphthalenes and cyclohexadienes:[78]



The insertion of CO has been observed when the reaction was carried out both in an atmosphere of carbon monoxide and in its absence. Other electrophiles also proved to be effective in the synthesis of 5,6-disubstituted cyclohexa-1,3-dienes.[9]

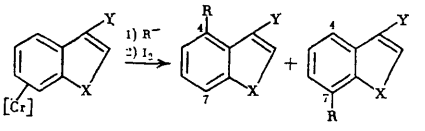
The ability of nucleophiles to add preferentially to the eclipsed carbon atoms of the arene liquid is manifested strikingly in the reactions of 1,1-disubstituted indan complexes.[66,80] The reactions of cyano-stabilised carbanions with the complexes (XXIX) and (XXX) and subsequent oxidation lead to 5-substituted indans:



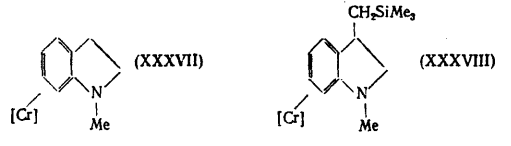


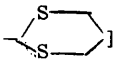
Hydrolysis of compound (XXXI) affords the pharmacologically valuable 5-substituted acid (XXXII). According to the results of X-ray diffraction analysis of the complex (XXX),[80] the CO groups are in the eclipsed conformation relative to the 3*a*, 5-, and 7-positions in the arene ligand.

The method involving the addition/oxidation of reactive *C*-nucleophiles to BCT has been extended to complexes of *N*-substituted indoles, *N*-methylindoline, and benzofuran.[81,82] The attack by the nucleophiles is then directed to C(4) and C(7) and the product ratio is regulated by electronic and steric factors determined by the size of the substituents at the nitrogen atom and C(3) and also by the nature of the nucleophile:

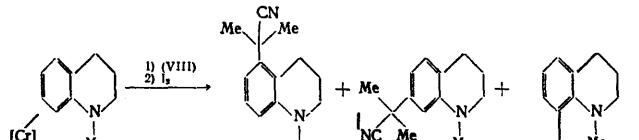


Compound (VIII) adds to the C(4) atom in the complexes with Y = H and X = NMe (XXXIII), NCH_2Ph (XXXIV), $NSiPh_2Bu$-t (XXXV), and NCO_2Bu-t (XXXVI) with a selectivity in excess of 90%. In the reaction of the complex (XXXIII), the less bulky anion $LiCH_2CN$ exhibits a lower selectivity [C(4)/C(7) = 75/25]. On the other hand, 2-lithio-1,3-dithiane and 1-lithio-3-dimethylsilylprop-2-ene reacts with the complex (XXXIII) preferentially at the C(7) atom, forming a mixture of substitution products [C(7)/C(4) = 6/1]. In contrast to the *N*-methylindole complex (XXXIII), the dithiane anion acts only on the C(4) atom in the *N*-methylindoline complex (XXXVII), which, bearing in mind the ease with which the indoline system can be converted into the indole system,

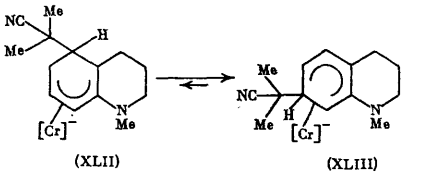


leads to the possibility of the selective synthesis of 4- and 7-substituted indoles. The addition of nucleophiles to the benzofuran complex is directed mainly to the C(4) position [C(4)/C(7) is 73/27 for R = CMe_2CN, 63/37 for R = CH_2CN, and 86/14 for R = ]. The introduction of substituents at the C(3) atom in the indole system reduces the yield of the 4-substituted product and, in the case of the complex (XXXVIII), for example, C(4)/C(7) = 17/83 for R = CMe_2CN. The opposite effect is produced by bulky substituents at the nitrogen atom [the complexes (XXXV) and (XXXVI)].

An elegant study of the reaction of (η^6-methyl-1,2,3,4-tetrahydroquinoline)ChTC with compound (VIII) revealed the influence of kinetic and thermodynamic control on the ratio of the regioisomers:[83]



The isomer (XLI) is formed in small amounts (1–2%) and the ratio of the isomers (XXXIX) and (XL) depends on the reaction time and temperature and also on the nature of the solvent, the increase of the relative content of the isomer (XL) when the reaction is carried out in THF indicating the thermodynamic control of the reaction, while the more highly substituted anion (XLII) is converted into the sterically more favourable anion (XLIII):

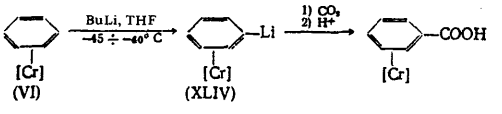


In the presence of added hexamethylphosphoramide (HMP), which strongly solvates the lithium cation, a constant ratio of the regioisomers, reflecting the kinetic control of the nucleophilic addition, is retained and in this instance there is no isomerisation. The combination of these results constitutes convincing evidence for the reversibility of the addition of nucleophiles to BCT.

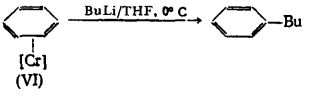
IV. REACTIONS OF LITHIO-DERIVATIVES

One of the most important properties of BCT is the increased acidity of the ring hydrogen atoms, which is the reason for their ability to be substituted by a metal on treatment with metallating agents. The nature of the metallating agent has a decisive influence on the direction of the process—soft nucleophiles add to the complex, while hard nucleophiles substitute a hydrogen atom.

The metallation of BCT was first achieved, by Nesmeyanov and co-workers, on treatment with BuLi; the yield of the acid after carboxylation was 19%:[84]

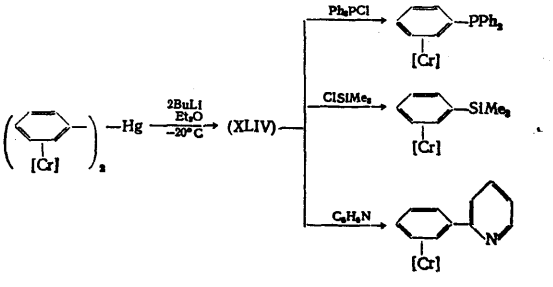


It has been shown[19,85–87] that BCT reacts with BuLi to form the complex (XLIV) almost quantitatively at −20 °C in THF but heating of the solution to 0 °C or the addition of BuLi to the BCT solution at 0 °C leads to butylbenzene in a yield greater than 80%:

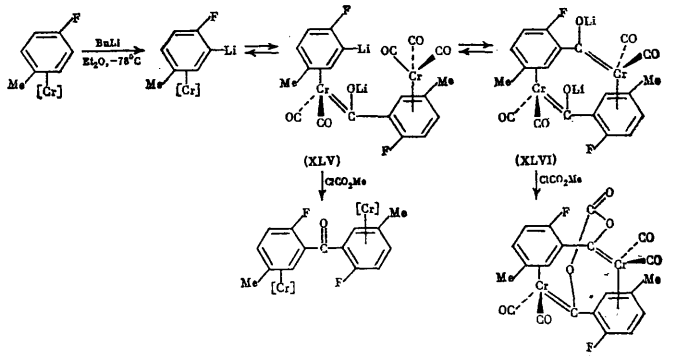


The oxidation stage is not then required. The mechanism of the formation of butylbenzene is obscure but it is undoubtedly different from the mechanism of the coupling of soft nucleophiles to BCT.

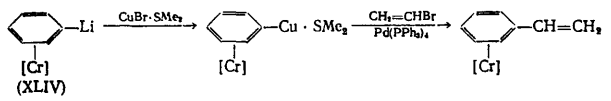
The lithio-BCT (XLIV) is readily obtained by the transmetallation reaction between dibenchrotrenylmercury and butyl-lithium and readily reacts with chlorophosphines, chlorosilanes, and pyridine:[88]



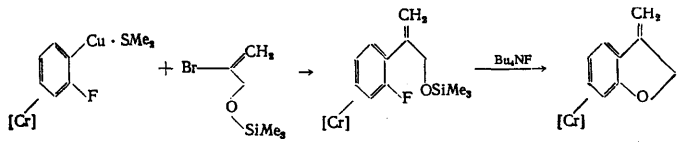
In relation to the metallation of (*p*-fluorotoluene)ChTC, it has been shown that the monomeric compounds of type (XLIV) formed at a low temperature are in equilibrium with the dimeric complexes (XLV) and (XLVI). This is manifested in reactions with electrophiles having more than one potential leaving group, for example, methyl chlorocarbonate, whereupon derivatives of benzophenone and carbonate are formed:[89]



A characteristic property of lithio-BCT is their anomalously low nucleophilicity compared with their basicity and the set of electrophiles which react with them is therefore limited.[87,90] Lithio-BCT do not react with propyl iodide and alkanesulphonates, giving rise to low yields of products even in reactions with active electrophiles such as MeCOCl and CH_2CHCH_2Br. It has been found[90] that the addition of the complex CuBr.SMe_2 to compound (XLIV) leads to copper-BCT, which react successfully with a large set of electrophiles, affording substitution products. The application of palladium catalysis made it possible to extend the scope of the reaction to include the products of cross-coupling with vinyl bromide and iodobenzene:

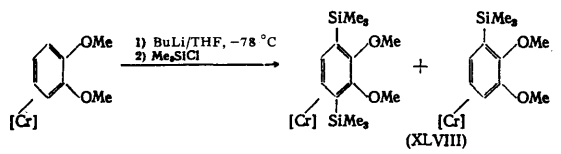


The reaction of (*o*-fluorophenyl-lithio)ChTC with the complex CuBr.SMe_2 and the subsequent coupling of the Cu-derivative with 2-bromoallyltrimethylsilyl ether give rise to the complex (XLVII), which undergoes intramolecular cyclisation, after desilylation, to the 3-methylene-2,3-dihydrobenzofuran complex:[91]



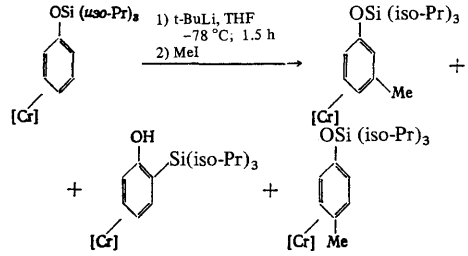
A characteristic feature of the latter is the lack of a tendency towards isomerisation to the 3-methylbenzofuran isomer, which is the product of the aromatisation of 3-methylene-2,3-dihydrobenzofuran not bound in a complex.

Metallation of (veratrole)ChTC by BuLi with subsequent silylation leads to a mixture of the mono- and di-silylated complexes in approximately equal amounts:[92]

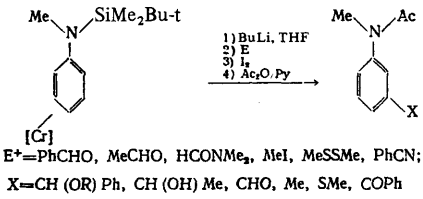


According to ^{1}H NMR and X-ray diffraction data, the complex (XLVIII) in solution and in the solid state has the conformation in which the bulky Me_3Si group is eclipsed by the CO group.[93]

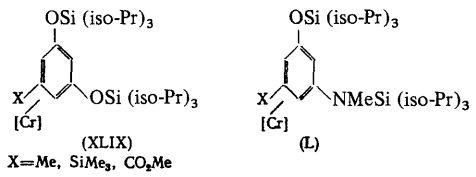
Protection of the hydroxy-group in (phenol)ChTC leads to marked shielding of the *o*-positions and the metallation takes place in the *m*-position to the extent of 90%.[94] The yield of the *o*-substituted product does not exceed 3%:



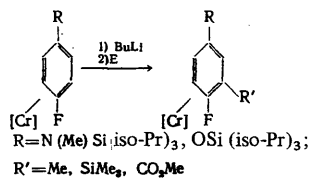
The methylation of (*N*-butyldimethylsilyl-*N*-methylaniline)-ChTC proceeds with a high regioselectivity in the *m*-position; *m*-substituted aniline can be obtained by subsequent reactions of the electrophile and the removal of ChTC.[95] The complete absence of *o*-substitution is noteworthy:



The substitution of resorcinol and *m*-aminophenol by lithium takes place exclusively in the 5-position, so that the 1,3,5-trisubstituted complexes (XLIX) and (L) are formed after reactions with electrophiles:



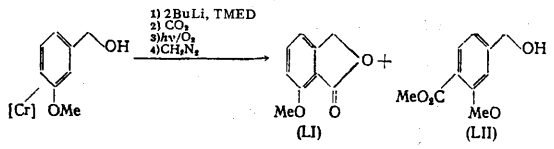
The metallation of tri-isopropylsilyl derivatives of *p*-fluorophenol and *p*-fluoroaniline, where the hydrogen atoms in the *o*-position relative to the fluorine atom are substituted, is especially noteworthy:



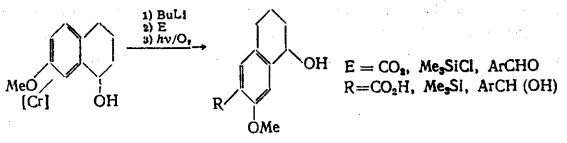
These results are the opposite to those of the metallation of sterically unhindered arenes and arenes not bound in a complex, for example, *p*-fluoroanisole and *p*-fluorodimethylaniline, where the metal always enters the *o*-position relative to the heteroatom.

The change in the regioselectivity of the metallation of the benzene ring after coordination to ChTC can be traced distinctly in relation to benzyl alcohols.[96,97] (3-Hydroxymethyl-1-methoxybenzene)ChTC reacts with two equivalents of BuLi to form the benzofuranone (LI) and the benzoic acid ester

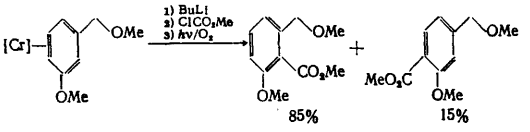
(LII) in proportions of 23 : 77 after carboxylation and methylation, while the analogous sequence of reactions with the arene not bound in a complex yields the ratio 9 : 1. With increase of the bulk of the metallating agent, the content of the 5-methylated product (LII) increases (85% for s-BuLi and 95% for t-BuLi):



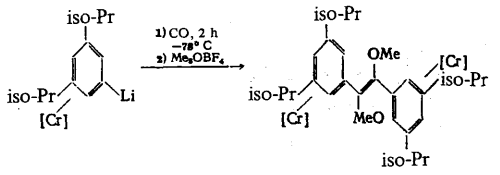
The coordination of a hard system, such as, for example, 7-methoxy-1-tetralinol, to ChTC leads to metallation exclusively in the 6-position, while the substitution of free tetralinol by lithium yields the 8-substituted product:



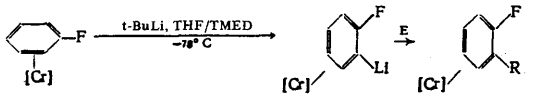
Alkyl benzyl ethers and the acetals of benzaldehydes are not *o*-metallated owing to the tendency towards deprotonation in the benzyl position with subsequent Wittig rearrangement or cleavage of the acetal linkage. The formation of a complex with TC makes it possible to metallate successfully the aromatic ring containing the above substituents with the predominant formation of 1,2,3-trisubstituted-products:



The reaction of *m*-di-isopropylbenchrotrenyl-lithium with CO and subsequent methylation with trimethyloxonium tetrafluoroborate lead to a dinuclear complex in 15% yield:[98]



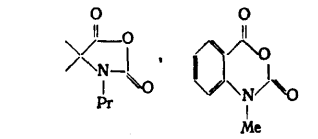
A novel application of the characteristic features of benchrotrenyl systems in synthesis has been achieved by Chavshow and Widdowson,[99] who showed that the metallation of the complex (III) results in the formation of (*o*-fluorolithiobenzene)ChTC (LIII), which react smoothly with various electrophiles; depending on the ratio of the substrate and the reactant, substitution products [Eqn.(2)] or cyclisation products [resulting from the simultaneous nucleophilic substitution of the fluorine atom—Eqn.(3)] are obtained:

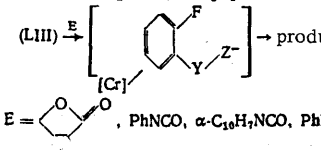


(2)

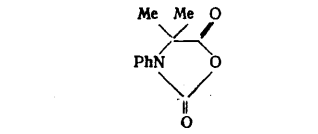
(III) (LIII)

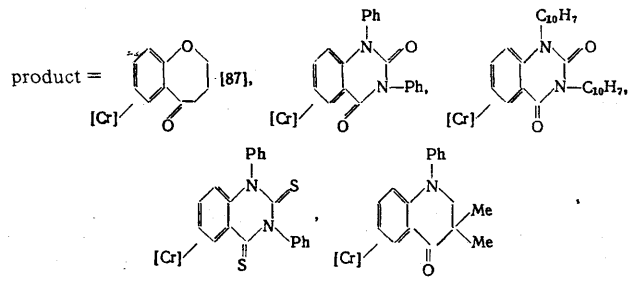
E=ClCO2Et, PhNCO, α-C10H7NCO, Ph2C=C=O,





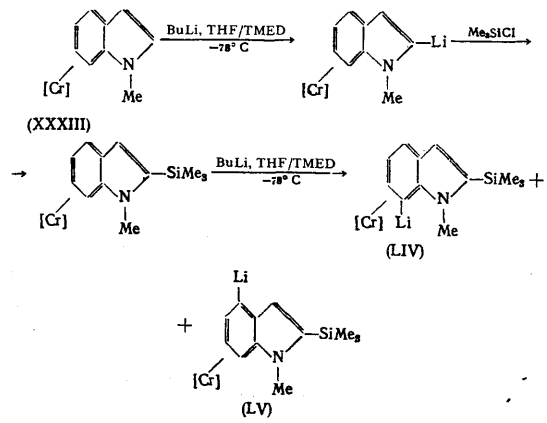
(3)





The method proposed for the synthesis of benzo-condensed systems may find an application in the chemistry of heterocyclic compounds.

The metallation of (1-methylindole)ChTC (XXXIII) occurs in the first place in the 2-position. If this position is occupied, then attack is directed to the aromatic ring in the 7- and 4-positions in the proportions ≥4 : 1:[100]

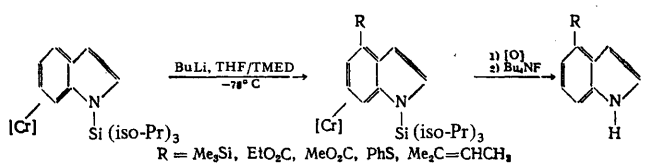


The reactions of the complexes (LIV) and (LV) with $ClCO_2Et$, MeI, PhCHO, $CH_2 = CHCHO$, PhSCl, and $Me_2C = CHCH_2Br$ followed by the chromatographic separation of the products, decomposition of the complexes, and desilylation have been recommended for the synthesis of 7-substituted indoles.

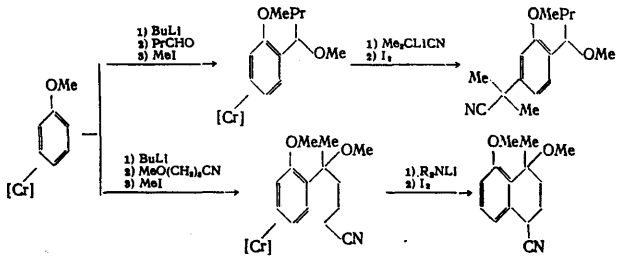
According to X-ray diffraction and ^1H NMR data, obtained in solution, the structure (XXXIII) corresponds to the direction of nucleophilic attack on the 4- and 7-positions in the ligand,[101] which is in the eclipsed conformation.

If the 1-position in (indole)ChTC contains the bulky triisopropyl group, then the metallation of the complex is directed mainly to the 4-position together with formation of a certain amount of 5- and 6-isomers.[102] Decomposition of the

complexes and desilylation lead to 4-substituted indoles in 70% yield:



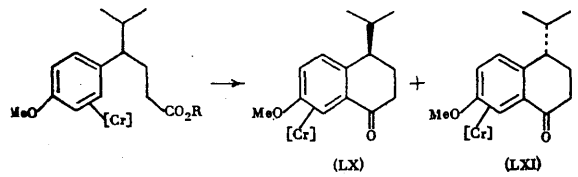
The metallation of BCT combined with nucleophilic addition or substitution has been used to synthesise trisubstituted benzenes: [87]



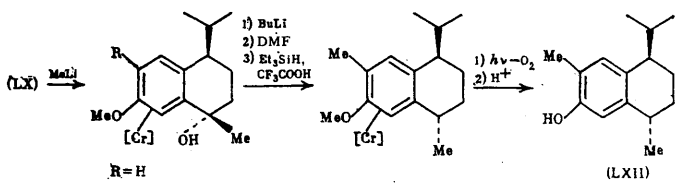
Favourable prospects for the employment of (lithioarene)-ChTC in synthesis, especially for the preparation of natural products, have become apparent. The synthesis of natural anthraquinones, namely 3-deoxyrabelomycin (LVI) and aclavinone (LVII), [103] is illustrated in Eqns.(4) and (5): [103]

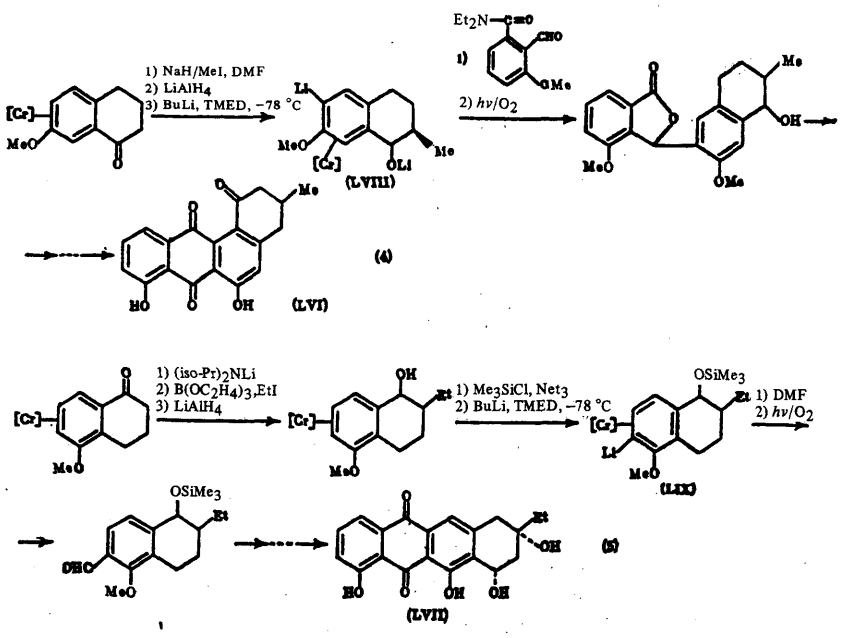
The metallation of the (tetralinol)ChTC complexes proceeds regioselectively, yielding the 6-lithio-derivatives (LVIII) and (LIX).

Temporary coordination to ChTC has been used in the synthesis of *cis*- and *trans*-7-hydroxycalamenenes. [104] The complex of 4-(*p*-methoxyphenyl)-5-methylhexanoate and $Cr(CO)_6$ was hydrolysed to the acid and the *exo*-isopropyltetralinone complex (LX) together with a small amount of the *endo*-isomer (LXI) were obtained by cyclising the acid chloride with $AlCl_3$:

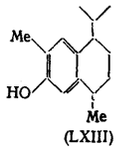


The reaction of the complex (LX) with MeLi leads to the *exo*-methylated product, which was metallated with BuLi in DMF and a benzaldehyde derivative was obtained. In the course of ionic hydrogenation, the reduction of the aldehyde functional group to the methyl group and hydride substitutior in the benzyl position were observed simultaneously:





Decomposition of the complex and *O*-demethylation lead to *trans*-7-hydroxycalamenene (LXII) in a satisfactory yield. *cis*-7-Hydroxycalamenene (LXIII) was obtained from the *endo*-complex (LXI) in accordance with an analogous scheme:

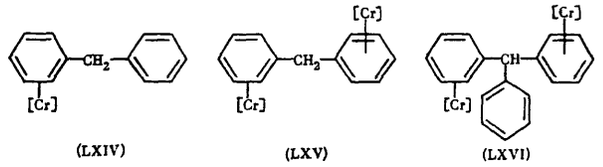


(LXIII)

V. BENZYL ACTIVATION OF ALKYL-SUBSTITUTED DERIVATIVES

The reduced electron density on the arene ligand in BCT is responsible for the considerable increase of the acidity of the benzyl hydrogen atoms. According to an approximate estimate, their acidity in BCT derivatives is greater by two orders of magnitude than the acidity of the corresponding hydrogen atoms in the substrate not bound in the complex.[105,106]

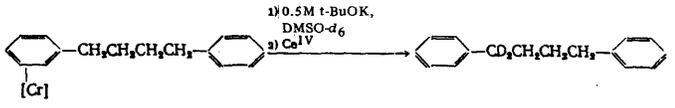
The acidifying effect of ChTC was estimated by measuring the rate of abstraction of a proton by the methoxide ion from the complexes (LXIV)–(LXVI) in the MeOH–Me_2SO system:



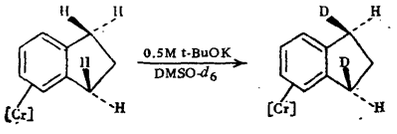
(LXIV) (LXV) (LXVI)

Actually their kinetic acidities are similar, which has been explained by the unfavourable steric influence of the second ChTC group in diphenylmethane on the rate of ionisation of the exocyclic CH bond. However, their thermodynamic acidities increase in proportions of 1 : 2.6 : 7.4, which reflects the greater stability of the carbanion formed following the introduction of electron-accepting groups.[107]

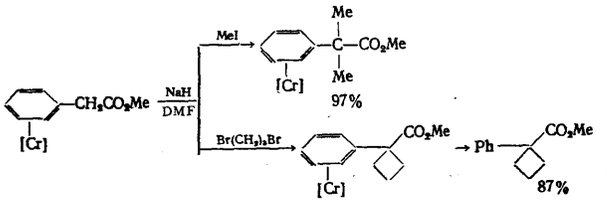
The α-hydrogen atoms of alkyl-BCT are involved in fairly rapid protophilic deuterium exchange; for example, (η^6-1,4-diphenylbutane)ChTC can be involved in the exchange with 0.5 M t-BuOK in DMSO-d_6 and after the decomposition of the complex affords 1,1-dideuterio-1,4-diphenylbutane:[108]



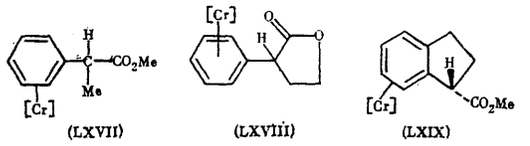
It is striking that (indan)ChTC exchanges only two of the benzyl protons, which constitutes convincing proof of the *exo*-attack by the base on the complex:



The effect of the formation of a complex with ChTC is strikingly manifested in the alkylation of phenylacetic acid esters and acetophenones.[20,109] Whereas methyl phenylacetate is not alkylated by MeI/NaH in DMF, its ChTC complex forms the dialkylated derivative almost quantitatively under these conditions and the reaction with 1,3-dibromopropene affords cyclobutane:



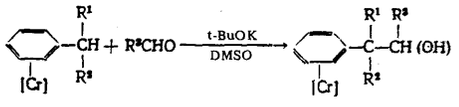
The complexes of the esters (LXVII)–(LXIX) are alkylated smoothly by the active alkyl halides RX (MeI, $PhCH_2Br$, $CH_2=CHCH_2Br$, and $HC\equiv CCH_2Br$) not only in the NaH/DMF system but also under the conditions of phase-transfer catalysis using cetyltrimethylammonium iodide:[110–112]



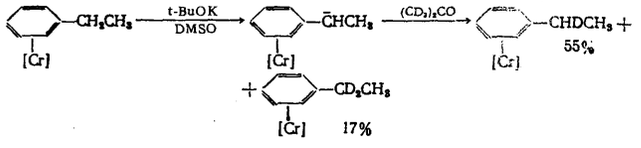
(LXVII) (LXVIII) (LXIX)

The stereochemistry of the reactions is virtually the same, the electrophile attacking from the side opposite to that of ChTC.

The reaction of alkyl-BCT with formaldehyde and benzaldehyde in the presence of t-BuOK in DMSO has been used to obtain β-hydroxy-compounds, but in many instances the preparative value of the method is low owing to the low yield of products:[113,114]

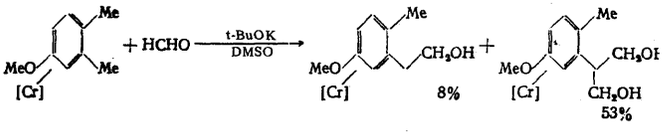


If the carbonyl compound is capable of giving rise to the enolic form, the arene complex enters only into the proton exchange reaction with formation of the corresponding alcohol:



The attack by the acyclic carbanion is stereospecific and gives rise to the *exo*-product only.

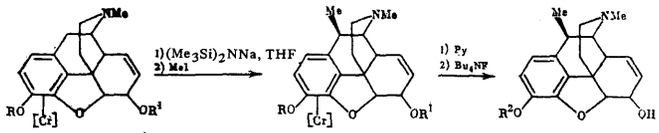
It has been shown[115] that, in the presence of an alkoxy-group in the benzene ring, there is a possibility of the selective formation of α-carbanions in the *m*-position, while *p*-alkyl groups are inert:



These features are responsible for the successful regio- and stereo-specific addition of formaldehyde and alkyl halides to alicyclic compounds, especially oestrogens.[115,116]

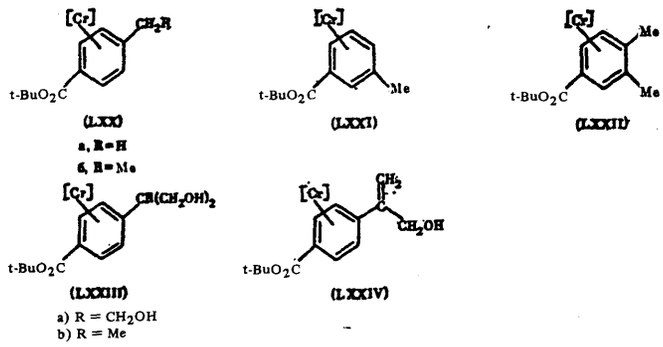
The interaction of [6-O-t-butyl(dimethyl)silylcodeine]ChTC and {3,6-bis[t-butyl(dimethyl)silyl]morphine}ChTC with $(Me_3Si)_2NNa$ and MeI leads to 10(*S*)-methyl derivatives. On subsequent decomposition of the complex with pyridine and

desilylation, 10(*S*)-methylcodeine and 10(*S*)-methylmorphine are formed smoothly respectively:[117]

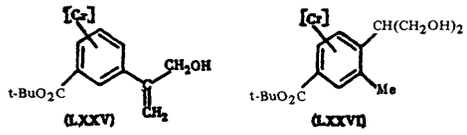


R = R^2 = Me, R^1 = t-BuMe$_2$Si; R = R^1 = t-BuMe$_2$Si, R^2 = H.

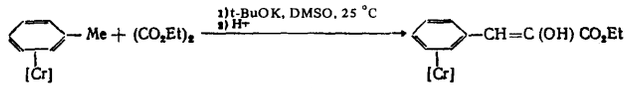
The presence of a strong electron-accepting group in the aromatic rings of the complexes alters the regioselectivity of the attack by the aldehyde in the presence of t-BuOK and activates the alkyl groups. For example, the diol, triol, and alkenol complexes (LXXIII)–(LXXVI) are formed from the complexes (LXX)–(LXXII) on reaction with formaldehyde:[118]



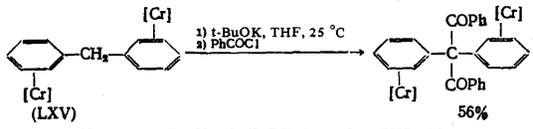
a) R = CH_2OH
b) R = Me



The reaction of (toluene)ChTC with t-BuOK in the presence of diethyl oxalate leads to a stable enol, derived from phenylpyruvic acid, whose structure has been demonstrated by X-ray diffraction:[119,120]

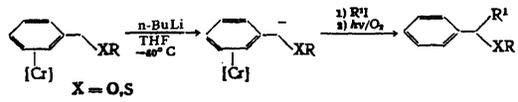


The α-protons in alkyl-BCT are readily abstracted in the reaction with t-BuOK in THF and the carbanions formed react with MeI,[121,122] diethyl oxalate and benzaldehyde,[123] and PhCOCl,[121] for example:

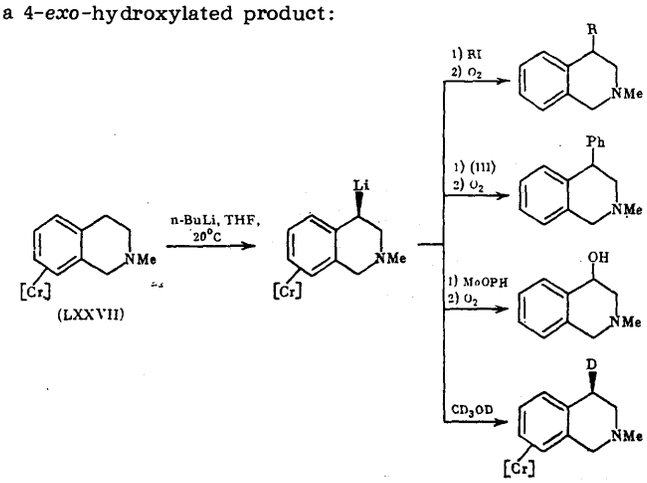


The α-metallation of alkyl-BCT by the KH/18-crown-6 ether system has been described.[124]

The α-metallation of certain BCT derivatives is achieved effectively with the aid of butyl-lithium and in this respect the ChTC derivatives of alkyl benzyl ethers and alkyl benzyl sulphides exhibit interesting features.[125] The α-carbanions derived from alkyl benzyl ethers and sulphides readily undergo the Wittig rearrangement, while coordination with ChTC leads to the possibility of achieving smoothly alkylation by various agents with formation, after the decomposition of the complex, of α-substituted benzyl ethers:

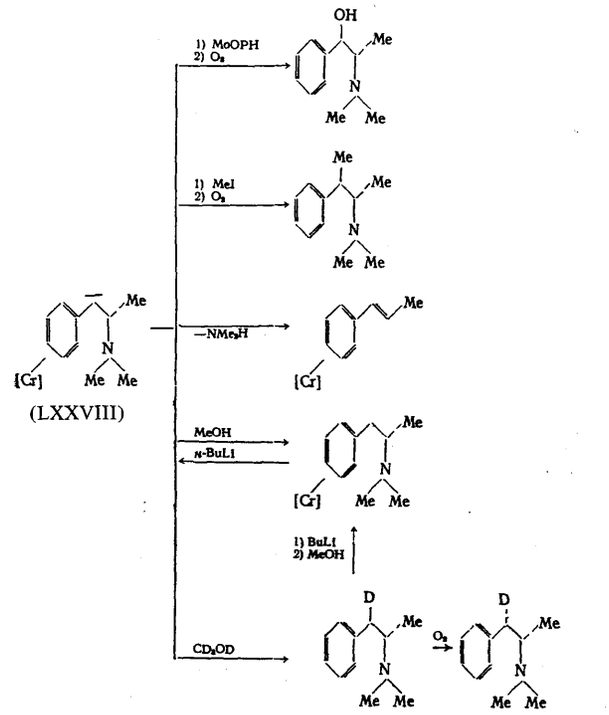


The formation of the transient complex between the aromatic ring and ChTC proved to be useful in the selective synthesis of 4-substituted 1,2,3,4-tetrahydroisoquinolines, which exhibit a selective pharmacological activity.[126] Metallation of the complex (LXXVII) leads to the substitution of the *exo*-hydrogen in the 4-position and the formation of a lithio-derivative, which is alkylated smoothly by alkyl halides, is phenylated by (fluorobenzene)ChTC, and reacts with oxodiperoxomolybdenumhexamethylphosphoramide (MoOPH) to form a 4-*exo*-hydroxylated product:



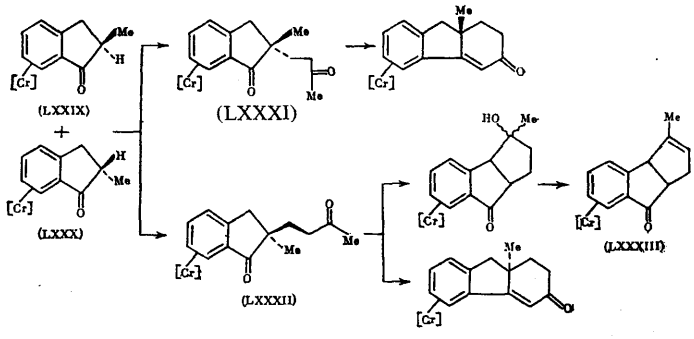
The coordination of *NN*-dimethylamphetamine to ChTC stabilises the corresponding benzyl carbanion in relation to the elimination of the amino-group and makes it possible to carry out smoothly stereospecific benzyl substitution.[127]

Metallation of the complex (LXXVIII) by n-BuLi at −40 °C and above leads to the elimination of Me_2NH and the formation of (*E*-β-methylstyrene)ChTC. However, at −78 °C the anion formed initially is stable and readily reacts with electrophiles (MeI, MoOPH, CD_3OD) to form derivatives of the complex (LXXVIII), from which free radicals are readily produced:

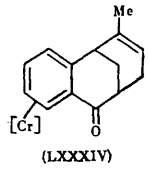


A notable feature of the above substitution reactions is their high stereospecificity.

The increased acidity of the α-hydrogen atoms in BCT constitutes the basis of the synthesis of certain condensed systems, modelling natural products, from indanone and tetralinone complexes.[128,129] Thus the diastereoisomers (LXXIX) and (LXXX), which exist in equilibrium in acid and basic media, readily undergo the Michael reaction with methyl vinyl ketone in the presence of 1,5-diazabicyclo[4.3.0]non-5-ene to form two adducts—the *exo*-adduct (LXXXI) and the *endo*-adduct (LXXXII) in proportions of 13 : 87. The complexes are able to undergo a base-catalysed cyclisation and compound (LXXXII) affords mainly (>90%) the products of cyclisation at the benzyl position, the unsaturated tricyclic system (LXXXIII) being obtained after dehydration:



The system (LXXXIV) has been obtained analogously from tetralinone complexes:

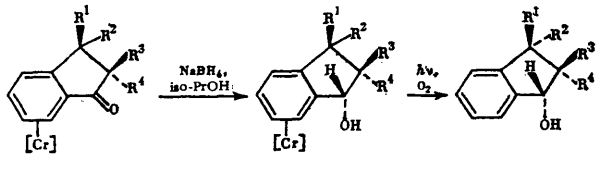


The, at first sight, anomalous *exo*-attack by the ketone on the benzyl position becomes readily explicable from the standpoint of the activating effect of ChTC on the hydrogen atom in the α-position. In view of the regioselective activation of the benzyl CH bond, the stereochemical control of the annelation reaction, and the ease of the regeneration of the arene ligand from its TC complex, the method is exceptionally useful for the synthesis of various optically active compounds.

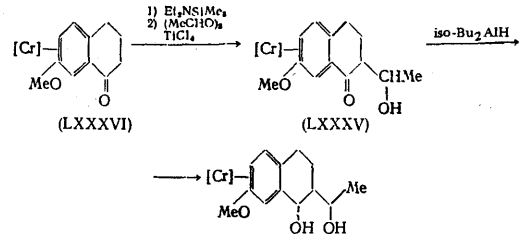
VI. STEREOCHEMICAL FEATURES OF ARENECHROMIUM TRICARBONYLS

The coordination of an arene to ChTC leads to the steric shielding of one of the sides of the aromatic ligand, which is the reason for the *exo*-attack by various agents on this ligand and for the direct binding of the functional groups with it.

The hydride reduction of (indanone)ChTC, (tetralinone)-ChTC,[130] and various (alkylindanone)ChTC (*exo* and *endo*-, α- and β-)[131–134] proceeds stereoselectively and leads to the formation of *endo*-alcohols. The amount of *exo*-alcohols did not exceed 10% in any one instance, amounting to 3% as a rule. Together with the quantitative decomposition of the complexes, this property provides an effective pathway to *cis*- and *trans*-indanols, for example:

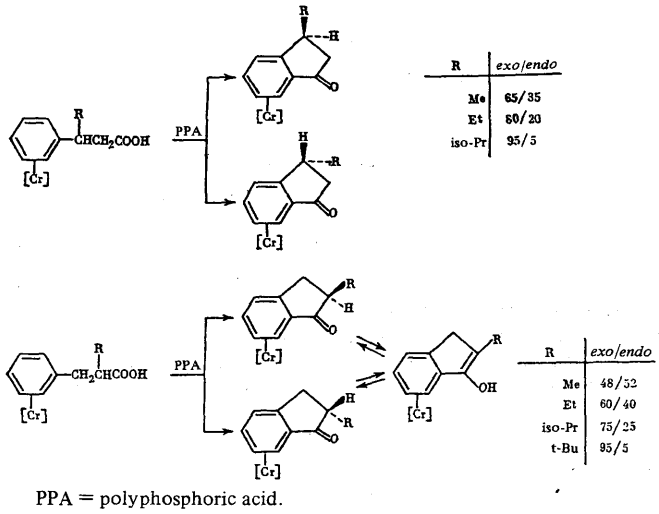


The reduction with di-isobutylaluminium hydride of the ketoalcohol (LXXXV), obtained by the reaction of the complex (LXXXVI) with diethyl-*N*-trimethylsilylamine in the presence of toluene-*p*-sulphonic acid and subsequent cross-aldol condensation with paraldehyde, affords only the *trans*-diol:[135]



In the absence of the ChTC group, a mixture of the *trans*- and *cis*-diols is formed in proportions of 12 : 88.

When the α- and β-alkyl-substituted benchrotrenylpropionic acids are cyclised, a definite regular behaviour is observed—the amount of *exo*-isomer increases with increase of the bulk of the substituent. The 2-indanone complexes formed can undergo the *exo* ⇌ *endo* transitions via the intermediate enolic form:[131,132]

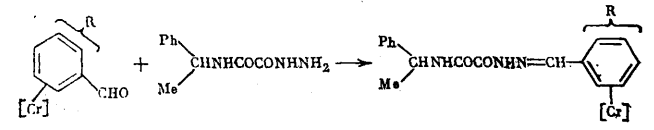


R	*exo*/*endo*
Me	65/35
Et	60/20
iso-Pr	95/5

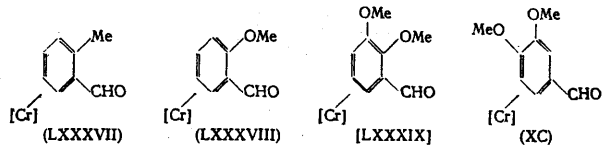
R	*exo*/*endo*
Me	48/52
Et	60/40
iso-Pr	75/25
t-Bu	95/5

PPA = polyphosphoric acid.

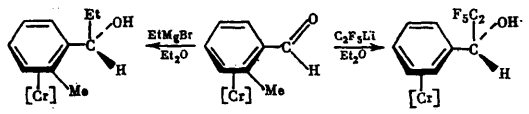
Chiral BCT with functional-group substituents, characterised by both planar and central chirality, are of special interest for asymmetric synthesis. BCT with two different substituents in the *o*- or *m*-positions are chiral and can be resolved into optical isomers.[136–143] For example, the resolution of the racemates of aldehydes has been achieved with a high yield via their reaction with (*S*)-(−)-5-(α-phenylethyl)-semioxamazide with subsequent chromatography. Acid hydrolysis results in the quantitative regeneration of the optically pure aldehydes:[144]



The aldehydes (LXXXVI)–(XC) have been resolved into the optically pure isomers by this method:

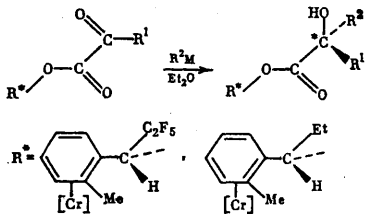


The reaction of the optically active aldehyde (LXXXVII) with ethylmagnesium bromide or perfluoroethyl-lithium gives rise to alcohols with an enantiomeric excess of 100 and 88% respectively:[145]



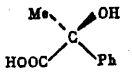
E.E. 100% (+)15-(LXXXVII) E.E. 88%

The chiral alcohols obtained were used in the Prelog type synthesis:

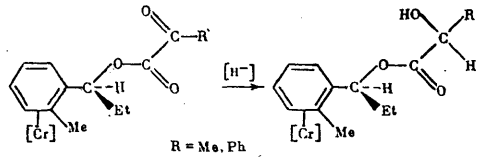


R^1 = Me, Ph; R^2 = C_2F_5, Me, PrC≡C, Ph

The asymmetric synthesis proceeds with a high enantiomeric excess (between 85 and 100%); for example, (+)-*S*-atrolactonic acid has been obtained by the addition of MeMgI to the optically pure ketoester and subsequent hydrolysis:

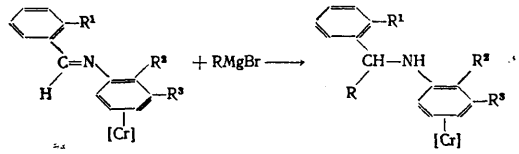


The reduction of a chiral α-ketoester by various reductants to α-hydroxyesters has been investigated:[146]



R = Me, Ph

A high percentage of asymmetric induction is observed when "L-selectide" $LiBH(Bu\text{-}s)_3$ is used as the reductant (E.E. = 84–90%). Just as high a degree of asymmetric induction has been obtained in reactions of Grignard reagents with complexes of aromatic Schiff bases (XCI):[147]

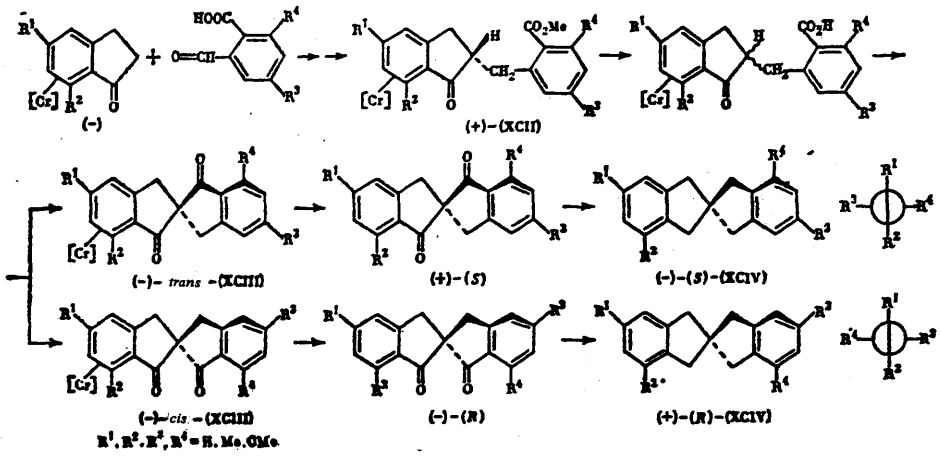


R = Me, $PhCH_2$;
R^1 = H, Me, OMe, Cl;
R^2 = H, Me, Et, Ph;
R^3 = H, Me

When an asymmetric Grignard reagent was allowed to react with (benzophenone)ChTC and (fluorenone)ChTC, partly resolved tertiary alcohols were obtained.[148]

The formation of complexes with ChTC had led to a simple and universal method of the synthesis of optically active benzospirans with a specific chirality from optically active (1-indanone)ChTC.[149,150]

The condensation of the complex with phthalic monoaldehyde [*o*-formylbenzoic acid?] produced a benzylidene complex from which the *endo*-benzyl derivative (XCII) was obtained after esterification and hydrogenation. On alkaline hydrolysis of the latter, epimerisation at the C(2) atom of the indanone was observed. Cyclisation of the complexes with polyphosphoric acid leads to a readily resolvable mixture of diastereoisomeric spiroindanone complexes—the *cis*- and *trans*-isomers of compound (XCIII). Optically active 2,2′-spirobi-indans (XCIV) were obtained by the decomposition of the complexes to 2,2′-spirobi-indan-1,1′-diones and subsequent catalytic hydrogenation:



(−) (+)-(XCII)

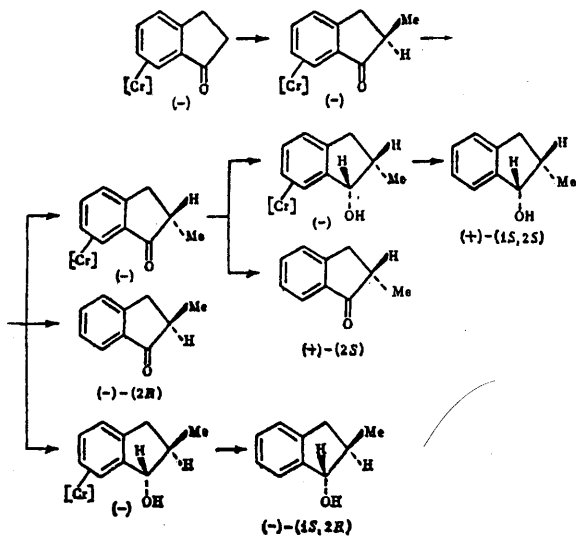
(−)-*trans*-(XCIII) (+)-(*S*) (−)-(*S*)-(XCIV)

(−)-*cis*-(XCIII) (−)-(*R*) (+)-(*R*)-(XCIV)

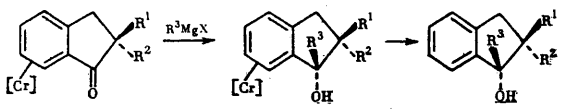
R^1, R^2, R^3, R^4 = H, Me, OMe

A cycle of reactions with the optically active complexes (I) and (II) has been carried out by Jaouen and Meyer.[151,152] The racemic compounds (I) and (II) were resolved into their enantiomers by the fractional crystallisation of the cinchonidinium salts of their acid succinates. Optically active indanone and tetralinone complexes are obtained by oxidising the corresponding alcohols with MnO_2 and the decomposition of the complexes of the enantiomers leads to optically active alcohols.

The *exo*-alkylation of the complexes in the 2-position leads to the formation of a new asymmetric centre in the system and creates a convenient preparative method of synthesis of optically active 2-methylindanones, 2-methyltetralinones, and the *trans*-alcohols. The possibility of obtaining the *cis*-alcohols from 2-methyl-*endo*-ketone complexes has been demonstrated in principle, although the separation of the *exo*- and *endo*-isomers requires a special technique. The reactions involved (indanone)ChTC, but all the characteristics are valid also for (tetralinone)ChTC:[151,152]

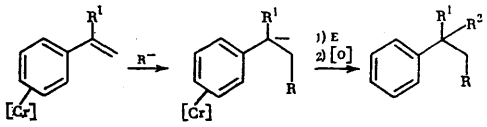


Taking into account the stereospecificity of the *exo*-attack by Grignard reagents on (indanone)ChTC and (tetralinone)-ChTC,[153] this method was used successfully to obtain optically active tertiary alcohols of the indan and tetralin series:

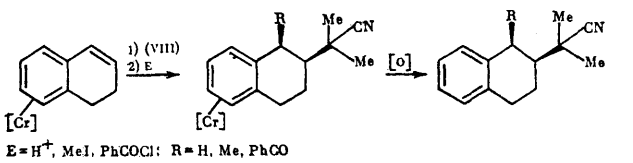


VII. OTHER REACTIONS

The reaction of vinyl-BCT with carbanions opens up wide prospects for organic synthesis.[154] It has been shown that a fairly large set of nucleophiles add to the β-position of the η^6-styrene ligand with formation of benzyl anions capable of being protonated or of reacting with electrophiles.[154] Decomposition of the complex leads to the formation of benzyl anions capable of being protonated or of reacting with electrophiles.[154] Decomposition of the complex leads to the formation of arenes with functional-group substituents:

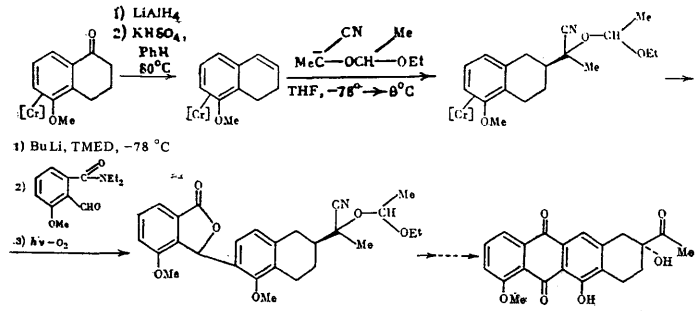


R^1 = H, Me, SEt; R = CMe_2CN, CMe_2CO_2Bu-t, Bu, Ph, Me, etc;
E = H^+, MeI, MeCOCl, PhSSPh; R^2 = H, Me, MeCO, PhS



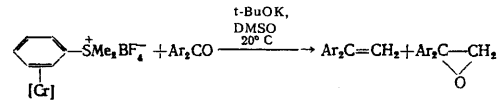
E = H^+, MeI, PhCOCl: R = H, Me, PhCO

The application of BCT to the synthesis of 11-deoxyanthracyclinones, exhibiting an anti-cancer activity, has been described.[155] The method is based on the characteristic features of the addition of the carbanion to alkenyl-BCT and on the regioselectivity of the metallation of the coordinated methoxyarene:



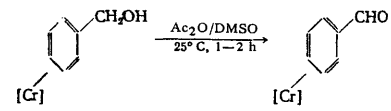
Among the practical aspects of the application of the BCT, mention should be made of their use as catalysts of the hydrogenation of dienes and polyenes[156,157] and as a label in molecular biology.[158–160]

On reaction with aldehydes and ketones, benchrotrenylsulphonium ylides form mixtures of an oxiran and an olefin, while purely organic sulphonium ylides produce only oxirans in this reaction:[161]

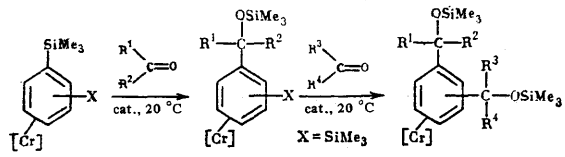


Preliminary results on the activating effect of the formation of complexes with ChTC on the oxidation of diphenylmethane to benzophenone have been published.[162] Whereas diphenylmethane is not oxidised by KO_2 in dimethyl sulphoxide, the complexes $(Ph_2CH_2)Cr(CO)_3$ and $(Ph_2CH_2)[Cr(CO)_3]_2$ are converted into benzophenone in 59 and 63% yields respectively.

A general method has been proposed for the oxidation of benchrotrenylcarbinols to aldehydes without the removal of ChTC, in 55–75% yield:[163]

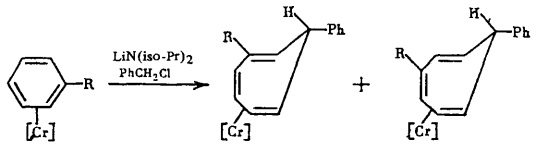


Mono- and bis-(trimethylsilyl)-BCT readily enter into reactions with aldehydes and ketones catalysed by t-BuOK or CsF, forming products of addition to the C=O groups:[164]



The electrochemical reduction of (benzophenone)ChTC, (benzophenone)$(ChTC)_2$, and (fluorenone)ChTC in the presence of 1,3-dibromopropane[165] and acetic or benzoic anhydride[166] has been recommended for the synthesis of diphenylmethyl derivatives.

The reaction involving ring expansion in the aromatic ligand in alkylbenchrotrenes on treatment with $PhCH_2Cl$ and lithium di-isopropylamide is of interest:[167]



According to X-ray diffraction data, the phenyl group has the *endo*-orientation. The reaction has been extended to Ph_2CHCl and $CH_2{=}CHCH_2Cl$.

REFERENCES

1. G.K.I.Magomedov, in "Metody Elementoorganicheskoi Khimii. Podgruppy Medi, Skandiya, Titana, Khroma, Margantsa. Lantanoidy i Aktinidy" (Methods of Organoelemental Chemistry. The Copper, Scandium, Titanium, Chromium, and Manganese Subgroups. Lanthanides and Actinides), Izd.Nauka, Moscow, 1974, Book 2, p.477.
2. W.E.Silverthorn, in "Advances in Organometallic Chemistry", Acad.Press, New York–London, 1975, Vol.13, p.48.
3. W.E.Watts, in "Comprehensive Organometallic Chemistry", Pergamon Press, Oxford, 1982, Vol.8, p.1013.
4. C.A.L.Mahaffy and P.L.Pauson, Inorg.Synth., 1979, **19**, 154.
5. C.A.L.Mahaffy, Synth.React.Inorg.Met.-Org.Chem., 1985, **15**, 155.
6. A.Solladie-Cavallo, Polyhedron, 1985, **4**, 901.
7. S.G.Davies, in "Organotransition Metal Chemistry. Applications to Organic Syntheses", Pergamon Press, Oxford, 1982, p.166.
8. J.P.Collman and L.S.Hegedus, "Principles and Applications of Organotransition Metal Chemistry", University Sci.Books, Mill Valley, 1980, p.651.
9. M.F.Semmelhack, J.Organometal.Chem.Library, Amsterdam, 1976, 1, 361.
10. M.F.Semmelhack, Ann.N.Y.Acad.Sci., 1977, **295**, 36.
11. G.Jaouen, Ann.N.Y.Acad.Sci., 1977, **295**, 59.
12. G.Jaouen, in "Transition Metal Organometallics in Organic Synthesis", Vol.2 (Edited by H.Alper), Acad. Press, New York–London, 1978, p.65.
13. M.F.Semmelhack, in "Organic Syntheses Today and Tomorrow" (Translated into Russian), Izd.Mir, Moscow, 1984, p.87.
14. M.F.Semmelhack, Pure Appl.Chem., 1981, **53**, 2379.
15. B.Nicholls and M.C.Whiting, J.Chem.Soc., 1959, 551.
16. F.van Meurs, A.J.Hoefnagel, B.M.Wepster, and H.van Bekkum, J.Organometal.Chem., 1977, **142**, 299.
17. A.Wu, E.R.Biehl, and P.C.Reeves, J.Chem.Soc., Perkins Trans II, 1972, 449.
18. A.Wu, E.R.Biehl, and P.C.Reeves, J.Organometal Chem., 1971, **33**, 53.
19. R.J.Card and W.J.Trahanovsky, Tetrahedron Letters, 1973, 3823.
20. G.Jaouen, A.Meyer, and G.Simmonneaux, Chem.Comm., 1975, 813.
21. G.Carganico, P.Del Buttero, S.Maiorana, and G.Riccardi, Chem.Comm., 1978, 989.
22. A.Pidcock, J.D.Smith, and B.W.Taylor, J.Chem. Soc.A, 1969, 1604.
23. A.A.Koridze, Uspekhi Khim., 1986, **55**. 277 [Russ. Chem.Rev., 1986(2)].
24. J.D.Holmes, D.A.Jones, and R.Pettit, J.Organometal. Chem., 1965, **4**, 324.
25. W.S.Trahanovsky and D.K.Wells, J.Amer.Chem.Soc., 1969, **91**, 5870.
26. A.Ceccon, J.Organometal.Chem., 1971, **29**, C19.
27. S.Top, B.Caro, and G.Jaouen, Tetrahedron Letters, 1978, 787.
28. S.Top and G.Jaouen, Chem.Comm., 1979, 224.
29. S.Top and G.Jaouen, J.Org.Chem., 1981, **46**, 78.
30. S.Top, A.Meyer, and G.Jaouen, Tetrahedron Letters, 1979, 3537.
31. S.Top and G.Jaouen, J.Organometal.Chem., 1980, **197**, 199.
32. S.Top, G.Jaouen, and M.McGlinchey, J.Chem.Comm., 1980, 1110.
33. M.Acampora, A.Ceccon, M.Dal Farra, G.Giacometti, and G.Rigatti, J.Chem.Soc., Perkin Trans.II, 1977, 483.
34. D.Seyferth and G.S.Eschbach, J.Organometal.Chem., 1975, **94**, C5.
35. D.Seyferth, J.S.Merola, and C.S.Eschbach, J.Amer. Chem.Soc., 1978, **100**, 4124.
36. M.Uemura, K.Isobe, and Y.Hayashi, Tetrahedron Letters, 1985, **26**, 767.
37. M.Uemura, T.Minami, and Y.Hayashi, J.Organometal. Chem., 1986, **299**, 119.
38. M.T.Reetz and M.Sauerwald, Tetrahedron Letters, 1983, **24**, 2837.
39. F.Goasmat, R.Dabard, and H.Patin, Tetrahedron Letters, 1975, 2359.
40. A.Meyer and G.Jaouen, J.Organometal.Chem., 1975, **97**, C21.
41. D.A.Brown and J.R.Raju, J.Chem.Soc.A, 1966, 40.
42. L.Tchissambon, G.Jaouen, and R.Dabard, Compt. rend.C, 1972, **274**, 806.
43. J.F.Bunnett and H.Hermann, J.Org.Chem., 1971, **36**, 4081.
44. V.V.Litvak, P.P.Kun, and V.D.Shteingarts, Zhur. Org.Khim., 1984, **20**, 753.
45. A.C.Knipe, S.J.McGuinness, and W.E.Watts, Chem. Comm., 1979, 842.
46. A.C.Knipe, S.McGuinness, and W.E.Watts, J.Chem. Soc., Perkin Trans.II, 1981, 193.
47. C.A.L.Mahaffy, Synth.React.Inorg.Met-Org.Chem., 1986, **16**, 61.
48. A.Alemagna, P.Del Buttero, C.Gorini, D.Landini, E.Licandro, and S.Maiorana, J.Org.Chem., 1983, **48**, 605.
49. A.Alemagna, C.Baldoli, P.Del Buttero, E.Licandro, and S.Maiorana, J.Org.Chem., 1983, **48**, 3114.
50. A.Alemagna, C.Baldoli, P.Del Buttero, E.Licandro, and S.Maiorana, Gazzetta, 1985, **115**, 555.
51. C.Baldoli, P.Del Buttero, S.Maiorana, and A.Papagni, Chem.Comm., 1985, 1181.
52. A.Alemagna, C.Baldoli, P.Del Buttero, E.Licandro, and S.Maiorana, Chem.Comm., 1985, 417.
53. M.Fukui, Y.Endo, and T.Oishi, Chem.Pharm.Bull., 1980, **28**, 3639.
54. R.P.Houghton and M.Voyle, Chem.Comm., 1980, 884.
55. R.P.Houghton, M.Voyle, and R.Price, J.Organometal. Chem., 1983, **259**, 183.
56. M.F.Semmelhack, G.R.Clark, J.L.Garcia, J.J.Harrison, Y.Thebtaranonth, W.Wulff, and A.Yamashita, Tetrahedron, 1981, **37**, 3957.
57. M.F.Semmelhack, H.T.Hall, R.Farina, M.Yoshifuji, G.R.Clark, T.Bargar, K.Hirotsu, and J.Clardy, J.Amer.Chem.Soc., 1979, **101**, 3535.
58. M.F.Semmelhack, H.T.Hall, M.Yoshifuji, and G.R.Clark, J.Amer.Chem.Soc., 1975, **97**, 1247.

59. M.F.Semmelhack, H.T.Hall, and M.Yoshifui, J.Amer. Chem.Soc., 1976, **98**, 6387.
60. M.F.Semmelhack, J.J.Harrison, and Y.Thebtaranonth, J.Org.Chem., 1979, **44**, 3275.
61. M.F.Semmelhack and G.R.Clark, J.Amer.Chem.Soc., 1977, **99**, 1675.
62. M.F.Semmelhack, G.R.Clark, R.Farina, and M.Saeman, J.Amer.Chem.Soc., 1979, **101**, 217.
63. T.A.Albright and K.B.Carpenter, Inorg.Chem., 1980, **19**, 3092.
64. A.Solladie-Cavallo and G.Wipff, Tetrahedron Letters, 1980, **21**, 3047.
65. A.Solladie-Cavallo and J.Suffert, J.Org.Magn.Reson., 1980, **14**, 426.
66. W.R.Jackson, I.D.Rae, M.G.Wong, M.F.Semmelhack, and J.N.Garcia, Chem.Comm., 1982, 1359.
67. M.F.Semmelhack, J.L.Garcia, D.Cortes, R.Farina, R.Hong, and B.K.Carpenter, Organometallics, 1983, 2, 467.
68. J.-C.Boutonnet, J.Levisalles, J.-M.Normant, and E.Rose, J.Organometal.Chem., 1983, **255**, C21.
69. M.F.Semmelhack and H.T.Hall, J.Amer.Chem.Soc., 1974, **96**, 7091.
70. M.F.Semmelhack and H.T.Hall, J.Amer.Chem.Soc., 1974, **96**, 7092.
71. J.-C.Boutonnet, F.Rose-Munch, and E.Rose, Tetradron Letters, 1985, **6**, 3989.
72. M.F.Semmelhack, Y.Thebtaranonth, and L.Keller, J.Amer.Chem.Soc., 1977, **99**, 959.
73. M.F.Semmelhack and A.Yamashita, J.Amer.Chem.Soc., 1980, **102**, 5924.
74. M.F.Semmelhack and A.Zask, J.Amer.Chem.Soc., 1983, **105**, 2034.
75. K.Schöllkopf, J.J.Stezowski, and F.Effenberger, Organometallics, 1985, **4**, 922.
76. E.P.Kündig, V.Desobry, and D.P.Simmons, J.Amer. Chem.Soc., 1983, **105**, 6962.
77. V.Desobry and E.P.Kündig, Helv.Chim.Acta, 1981, **64**, 1288.
78. E.P.Kündig, and D.P.Simmons, Chem.Comm., 1983, 1320.
79. E.P.Kündig, P.Paglia, and D.P.Simmons, in "Abstracts of XIIth International Conference on Organometallic Chemistry", Vienna, 1985, p.141.
80. J.-C.Boutonnet, L.Mordenti, E.Rose, O.Martret, and G.Preeigoux, J.Organometal.Chem., 1981, **221**, 147.
81. A.P.Kozikowski and K.Isobe, Chem.Comm., 1978, 1076.
82. M.F.Semmelhack, W.Wulff, and J.L.Garcia, J.Organometal.Chem., 1982, **240**, C5.
83. B.Ohlsson and C.Ullenius, J.Organometal.Chem., 1984, **267**, C34.
84. A.N.Nesmeyanov, N.E.Kolobova, K.N.Anisimov, and Yu.V.Markarov, Izv.Akad.Nauk SSSR, Ser.Khim., 1969, 2665.
85. R.J.Gard and W.S.Trahanovsky, J.Org.Chem., 1980, **45**, 2555.
86. R.J.Gard and W.S.Trahanovsky, J.Org.Chem., 1980, **45**, 2560.
87. M.F.Semmelhack, J.Bisaha, and J.Czarny, J.Amer. Chem.Soc., 1979, **101**, 768.
88. M.D.Rausch and R.E.Gloth, J.Organometal.Chem., 1968, **153**, 59.
89. L.M.Sandilands, C.J.L.Lock, R.Faggiani, N.Hao, B.G.Sayer, M.A.Quilliam, B.E.McCarry, and M.J.McGlinchey, J.Organometal.Chem., 1982, **224**, 267.
90. P.J.Beswick, S.J.Leach, N.F.Masters, and D.A.Widdowson, Chem.Comm., 1984, 46.
91. P.J.Beswick and D.A.Widdowson, Synthesis, 1985, 1985, 492.
92. J.-C.Boutonnet, J.Levisalles, F.Rose-Munch, E.Rose, G.Precigeoux, and F.Leroy, J.Organometal.Chem., 1985, **290**, 153.
93. J.-C.Boutonnet, F.Rose-Munch, E.Rose, Y.Jeannin, and F.Kobert, J.Organometal.Chem., 1985, **297**, 185.
94. N.F.Masters and D.A.Widdowson, Chem.Comm., 1983, 955.
95. M.Fukui, T.Ikeda, and T.Oishi, Tetrahedron Letters, 1982, **23**, 1605.
96. M.Uemura, N.Nishikawa, and Y.Hayashi, Tetrahedron Letters, 1980, **21**, 2069.
97. M.Uemura, N.Nishikawa, K.Take, M.Ohnishi, K.Hirotsa, T.Higuchi, and Y.Hayashi, J.Org.Chem., 1983, **48**, 2349.
98. J.-C.Boutonnet, F.Rose-Munch, E.Rose, and G.Precigoux, J.Organometal.Chem., 1985, **284**, C25.
99. M.Chavshow and D.A.Widdowson, J.Chem.Soc., Perkin Trans.I, 1983, 3065.
100. G.Nechvatal, D.A.Widdowson, and D.Williams, J.Chem. Comm., 1981, 1260.
101. J.-C.Boutonnet, F.Rose-Munch, E.Rose, and G.Precigoux, J.Organometal.Chem., 1985, **284**, C25.
102. G.Nechvatal and D.A.Widdowson, Chem.Comm., 1982, 467.
103. M.Uemura, K.Take, and Y.Hayashi, Chem.Comm., 1983, 858.
104. M.Uemura, K.Isobe, K.Take, and Y.Hayashi, J.Org. Chem., 1983, **48**, 3855.
105. A.Ceccon and G.Catelani, J.Organometal.Chem., 1974, **72**, 179.
106. A.Ceccon, J.Organometal.Chem., 1974, **72**, 189.
107. F.Terrier, P.G.Farrell, J.Lelievre, S.Top, and G.Jaouen, Organometallics, 1985, **4**, 1291.
108. W.S.Trahanovsky and R.J.Card, J.Amer.Chem.Soc., 1972, **94**, 2897.
109. G.Simmonneaux and G.Jaouen, Tetrahedron, 1979, **35**, 2249.
110. M.A.Boudeville and H.des Abbayes, Tetrahedron Letters, 1975, 2727.
111. H.des Abbayes and M.A.Boudeville, Tetrahedron Letters, 1976, 1189.
112. H.des Abbayes and M.A.Boudeville, J.Org.Chem., 1979, **42**, 4104.
113. J.Brocard, J.Lebibi, and D.Couturier, Chem.Comm., 1981, 1264.
114. J.Lebibi, J.Brocard, and D.Couturier, Bull.Soc. chim.France, 1983, 357.
115. G.Jaouen, S.Top, A.Laconi, D.Couturier, and J.Brocard, J.Amer.Chem.Soc., 1984, **106**. 2207.
116. S.Top, A.Vessieres, J.-P.Abjean, and G.Jaouen, Chem.Comm., 1984, 428.
117. H.B.Arzeno, D.H.R.Barton, S.G.Davies, X.Lusinchi, B.Meunier, and C.Pascard, Nouv.J.Chem., 1980, **4**, 369.
118. J.Brocard, A.Laconi, D.Couturier, S.Top, and G.Jaouen, Chem.Comm., 1984, 475.
119. B.Caro, J.-I.Le Bihan, J.-P.Guillot, and G.Jaouen, Chem.Comm., 1984, 602.
120. J.-F.Halet, J.-I.Saillard, B.Caro, J.-I.Le Bihan, S.Top, and G.Jaouen, J.Organometal.Chem., 1984, **267**, C37.
121. G.Jaouen, S.Top, and M.J.McGlinchey, J.Organometal Chem., 1980, **195**, C5.
122. N.A.Ustynyuk, Yu.F.Oprunenko, S.G.Malygina, O.I.Trifonova, and Yu.A.Ustynyuk, J.Organometal. Chem., 1984, **270**, 185.

123. M.C.Senechal-Tocquer, D.Senechal, J.-Y.Le Bihan, D.Gentric, and B.Caro, J.Organometal.Chem., 1985, **291**, C5.
124. A.Ceccon, A.Grambaro, and A.Venro, J.Organometal. Chem., 1984, **275**, 209.
125. S.G.Davies, N.J.Holman, C.A.Laughton, and B.E.Mobbs, Chem.Comm., 1983, 1316.
126. J.Blagg, S.G.Davies, and B.E.Mobbs, Chem.Comm., 1985, 619.
127. J.Blagg and S.G.Davies, Chem.Comm., 1985, 653.
128. G.Jaouen and A.Meyer, Tetrahedron Letters, 1976, 3547.
129. A.Meyer and O.Hofer, J.Amer.Chem.Soc., 1980, **102**, 4410.
130. W.R.Jackson and T.R.B.Mitchell, J.Chem.Soc.B, 1969, 1228.
131. G.Jaouen, B.Caro, and J.-Y.Li Bihan, Compt.Rend.C, 1972, **274**, 902.
132. B.Caro and G.Jaouen, J.Organometal.Chem., 1982, **28**, 87.
133. B.Caro and G.Jaouen, J.Organometal.Chem., 1981, **220**, 309.
134. B.Caro and G.Jaouen, Tetrahedron Letters, 1974, 1229.
135. M.Uemura, N.Nishikawa, S.Tokuyama, and Y.Hayashi, Bull.Chem.Soc.Japan, 1980, **53**, 293.
136. A.Mandelbaum, Z.Neuwirth, and M.Cais, Inorg.Chem., 1963, **2**, 902.
137. H.Falk, K.Sihlögl, and W.Steyrer, Monatsh.Chem., 1966, **97**, 1029.
138. R.Dabard and A.Meyer, Compt.Rend.C, 1967, **264**, 903.
139. R.Dabard and A.Mayer, Compt.Rend.C, 1969, **268**, 201.
140. G.Jaouen, L.Tissambou, and R.Dabard, Compt.Rend.C, 1972, **274**, 654.
141. R.Dabard and G.Jaouen, Tetrahedron Letters, 1968, 3391.
142. G.Jaouen and R.Dabard, J.Organometal.Chem., 1970, **21**, P.43.
143. K.R.Stewart, S.L.Levine, and J.Bordner, J.Org. Chem., 1984, **49**, 4082.
144. A.Solladie-Cavallo, G.Solladie, and E.Tsamo, J.Org. Chem., 1979, **44**, 4189.
145. A.Solladie-Cavallo and J.Suffert, Tetrahedron Letters, 1984, **25**, 1897.
146. A.Solladie-Cavallo and J.Suffert, Tetrahedron Letters, 1985, **26**, 429.
147. A.Solladie-Cavallo and E.Tsamo, J.Organometal.Chem., 1979, **172**, 165.
148. C.Mioskowski, A.Solladie-Cavallo, and G.Solladie, J.Organometal.Chem., 1978, **149**, C63.
149. A.Meyer, H.Neudeck, and K.Schlögl, Tetrahedron Letters, 1976, 2233.
150. A.Meyer, H.Neudeck, and K.Schlögl, Chem.Ber., 1977, **110**, 1403.
151. G.Jaouen and A.Meyer, J.Amer.Chem.Soc., 1975, **97**, 4667.
152. A.Meyer and G.Jaouen, Chem.Comm., 1974, 787.
153. A.Meyer and R.Dabard, J.Organometal.Chem., 1972, **36**, C38.
154. M.F.Semmelhack, W.Seufert, and L.Keller, J.Amer. Chem.Soc., 1980, **102**, 6586.
155. M.Uemura, T.Minami, and Y.Hayashi, Chem.Comm., 1984, 1193.
156. M.Cais, Chim.Ind.(Milan), 1979, **61**, 395.
157. J.R.Tucker and D.P.Riley, J.Organometal.Chem., 1985, **279**; 49.
158. W.Tondu, S.Top, A.Vessiers, and G.Jaouen, Chem. Comm., 1985, 326.
159. G.Jaouen, A.Vessieres, S.Top, A.A.Ismail, and L.S.Butler, J.Amer.Chem.Soc., 1985, **107**, 4778.
160. S.Top, G.Jaouen, A.Vessiers, J.-P.Abjean, D.Davonst, C.A.Rodeger, B.G.Sayer, and M.McGlinchey, J.Organometallics, 1985, **4**, 2143.
161. A.Ceccon, F.Miconi, and A.Venzo, J.Organometal. Chem., 1979, **181**, C4.
162. S.Top, G.Jaouen, and M.J.McGlinchey, Chem.Comm., 1980, 643.
163. S.G.Levine and B.Gopalakrishnan, Tetrahedron Letters, 1982, **23**, 1239.
164. F.Effenberger and K.Schöllkopf, Angew.Chem.Int. Ed., 1981, **20**, 266.
165. G.Degrand, F.Gasquez, and P.L.Compagnon, J.Organometal.Chem., 1985, **280**, 87.
166. C.Degrand, M.Bikrani, and B.Gautheron, J.Organometal.Chem., 1986, **299**, 111.
167. G.Simmonneaux, G.Jaouen, and R.Dabard, Tetrahedron, 1980, **36**, 893.

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