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β-Aminosubstituted α,β-unsaturated Fischer carbene complexes as chemical multitalents

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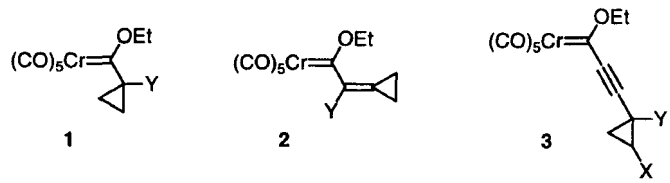
Abstract. – β-Aminosubstituted α,β-unsaturated Fischer carbene complexes of types **6/7/8** and **21** are readily available in two steps or even a single-pot operation from hexacarbonylchromium and the appropriate alkyne **4** via the alkynyl-substituted complexes **5** by Michael type addition of a secondary (primary) amine or ammonia. With the right choice of substituents and reaction conditions, they can selectively react to give 2*H*-pyrroles **20** (ref. 17), 5-dialkylamino-3-alkoxycyclopenta-1,3-dienes **42** (which are synthetic equivalents of cyclopentenones and even cyclopentadienones) (refs. 29,31), pyridines **25** (ref. 19), 5-(1'-dialkylaminoalkenylidene)-4-ethoxycyclopent-2-enones **32** (ref. 25), 2-(1'-dialkylamino-1'-alkenyl)cyclopent-2-enones **38** (ref. 27), 2-acyl-3-dialkylaminocyclopent-2-enones **33** (ref. 26) and cyclopenta[*b*]pyrans **26** (refs. 20,23).

INTRODUCTION

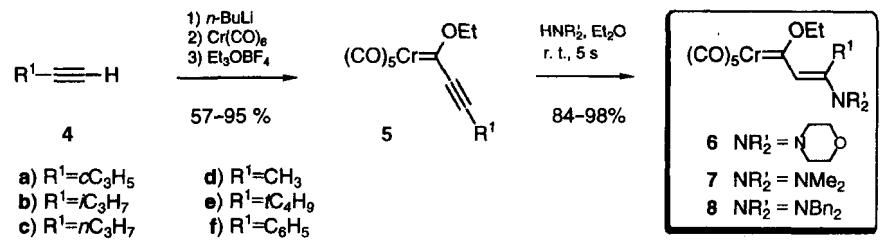
Although the reactions of Fischer carbene complexes are multifacetted and may therefore appear puzzling, they have become an important factor in the repertoire of organometallic transformations applied in organic synthesis (ref. 1). Especially the discovery of the formal cycloaddition of alkynes to α,β-unsaturated carbene complexes with carbonyl insertion – the so-called Dötz reaction – leading to hydroquinone monoethers (ref. 2) or cyclohexadienones (ref. 3), has triggered a drastic increase in research activities to exploit this rich chemistry. According to a recent survey, at least twenty-one different types of products have been obtained from phenyl- and alkenyl-substituted complexes of group VI metals in reactions with alkynes (ref. 4). And the popularity of them is still rising, as many of these product types are carbo- and heterocyclic systems, easily and efficiently assembled in the coordination sphere of the metal, but not otherwise. In view of previous experience which has shown that some of the slightest changes in the substituent nature and substitution pattern on the carbene ligand, in the reactant alkyne, as well as in the reaction conditions may lead to a change of the product type, it is evident that even more new reaction modes will be discovered. But in spite of this dazzling variability, most of these reactions eventually lead to a single type of product under an appropriate set of conditions.

CYCLOPROPYL-SUBSTITUTED CARBENE COMPLEXES

The reactivity of carbenepentacarbonylmetal complexes in general is best described with the carbonyl group analogy (ref. 5). The carbon metal bond in such a complex is polarized to a much greater extent than the carbon oxygen double bond in a carbonyl group. The positive end is on the carbon, which thereby is extremely electrophilic, while the metal center is nucleophilic. This led us to conceive cyclopropyl-substituted Fischer carbene complexes of types **1**, **2**, and **3** (ref. 6), in which the cyclopropyl group or the adjacent multiple bond should be activated toward nucleophilic attack, and hence such novel complexes would disclose interesting new chemistry. Indeed, soon after we started to work towards these complexes (ref. 7), Herndon et al. demonstrated the first example of the wealth of compounds of type **1** (ref. 8), and we therefore concentrated on types **2** and **3**. This report will be focussed on the chemistry of (2-cyclopropylethynyl)-substituted complexes of type **3**, their alkylethynyl analogues and especially α,β-unsaturated complexes derived from them by Michael type additions of amino nucleophiles (refs. 9,10).



Complex **5a** (≙**3** with X,Y=H) was easily assembled from cyclopropylacetylene and hexacarbonylchromium according to the standard procedure (ref. 11) in 65% yield (ref. 9). This complex was first tested as a dienophile, and indeed it underwent cycloaddition to cyclopentadiene at ambient temperature (73% yield) while the corresponding carboxylate did not add to cyclopentadiene even at elevated temperature. However, the cycloadduct ester could easily be prepared by oxidation of the cycloadduct carbene complex with DMSO (75%). Surprisingly, complex **5a** preferentially underwent [2+2] cycloaddition with 2-trimethylsilyloxybuta-1,3-diene rather than [4+2] cycloaddition (ref. 6). An analogous [2+2] cycloaddition of an alkynyl-substituted carbenechromium complex to enol ethers was simultaneously described by Wulff et al. (ref. 12). Following-up on these observations, we attempted the corresponding [2+2] cycloaddition to an enamine. However, when complex **5a** was treated with 1-morpholinylcyclohexene, a complex reaction mixture was obtained, in which the β-morpholinyl-substituted complex **6a** was a major component. It was probably formed by 1,4-addition of some morpholine contained in the starting material due to partial hydrolysis of the enamine. In fact, this Michael addition of morpholine to **5a** was brought about in 90% yield, and the corresponding dimethylamine adduct **7a** was obtained in 96% yield. This type of 1,4- addition

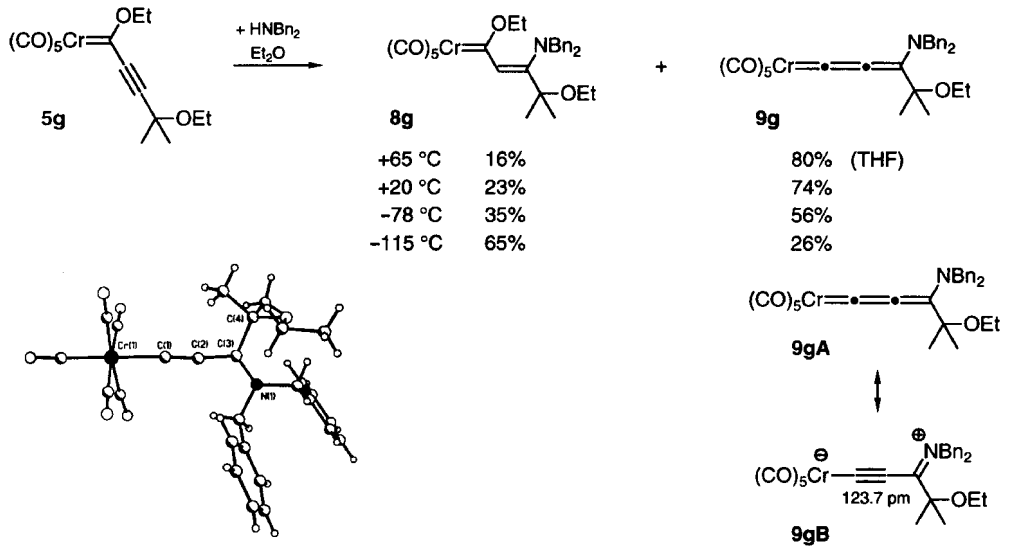


Scheme 1. Easy access to β-dialkylamino α,β-unsaturated carbene chromium complexes.

of a secondary amine to an alkynyl-substituted carbenechromium complex had previously been described by Fischer et al. (ref. 13), but only for a single example without clarification of the double bond configuration. As no follow-up chemistry of these interesting α,β-unsaturated complexes had been reported either, we first studied the Michael addition of various secondary and primary amines to a variety of alkynyl-substituted complexes **5a-f**, easily assembled from the corresponding alkynes **4a-f** (57–95% yield).

1,4-ADDITION OF AMINES TO ALKYNYLIDENECARBENE COMPLEXES

The addition of dimethylamine in ether solution to compounds **5** gave complexes **7** in virtually quantitative yields (Scheme 1). In most cases, except when R on the alkynyl terminus is extremely bulky, complexes **6/7** have an (*E*)-configurated double bond (ref. 9). The observation by Fischer et al. (ref. 13) that the 1,4-addition of dimethylamine is thermodynamically controlled, while 1,2-addition occurs under kinetic control at low temperature (–115 °C), turned out to be limited to the observed case (ref. 9). Depending on the bulkiness of the secondary amine, another temperature dependent side reaction was observed (ref. 10). For instance, the predominant product from the reaction of complex **5g** and dibenzylamine at room temperature was the (dibenzylaminoalkenylidene)chromium complex **9g** (74%), resulting from addition-elimination, rather than the 1,4-adduct **8g**. The latter was the preferred product only at –115 °C (65%). The structure of compound **9g** was proved by an X-ray crystal structure analysis (see Scheme 2). According to this, the bonding in **9g** is best described with a resonance hybride, in which the zwitterionic form **9gB** has a substantial weight.

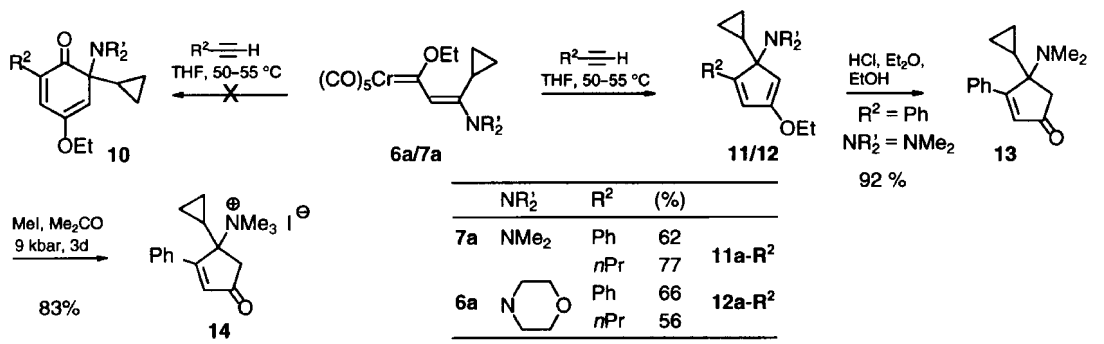


Scheme 2. 1,4-Addition versus 1,4-add./1,2-elim. to give 3-aminoallenylidene complexes **9g**.

The ratio between products **8g** and **9g** also depends on the bulk of the substituent R on the alkynyl terminus and on the bulk of the secondary amine. With primary isopropylamine, the addition-elimination product of type **9** prevails. The latter, which can be predicted to have an interesting chemistry of their own, can be made the only products by reacting alkynyl-substituted complexes **5** with lithium amides (both secondary and primary) instead of the free amines (ref. 10).

CYCLOADDITIONS OF ALKYNES TO (3-AMINOALKENYLIDENE)CHROMIUM COMPLEXES

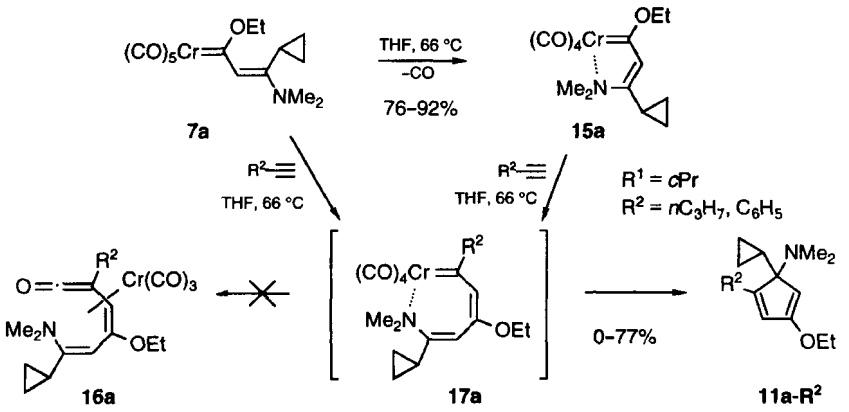
Being α,β-unsaturated carbene complexes, compounds **6/7/8** were anticipated to react with alkynes in the usual sense (refs. 2,3) with carbonyl insertion to give ethoxycyclohexadienones of type **10**. However, such products were not even detected in trace amounts from complexes **6a/7a**, they rather reacted without carbonyl insertion to give 5-dialkylaminocyclopentadienes **11/12** (Scheme 3). In view of the fact that all the known methods to make five-membered rings are limited in their applicability, this new assembly of highly functionalized cyclopentadienes of type **11/12** was rather welcome. After all, compounds **11/12** are protected cyclopentenones, they can in fact easily be hydrolyzed under acidic conditions to give 4-dialkylaminocyclopent-2-enones of type **13** (92%) (ref. 14). Since the tertiary amino group can be quaternized, albeit only under high pressure, the resulting quaternary ammonium salts of type **14** should be susceptable to a Hofmann elimination. In essence then, aminocyclopentadienes of type **11/12** would correspond to otherwise inaccessable cyclopentadienones.



Scheme 3. A formal [3+2] cycloaddition to give highly substituted cyclopentadienes **13**.

As far as the mechanism is concerned, this new reaction is initiated in the same way as the classical Dötz reaction by carbonyl to alkyne ligand exchange, followed by alkyne insertion to give the 1-chroma-1,3,5-triene of type **17** (ref. 14). This 1-metallatriene apparently prefers to undergo a 6π-electrocyclization to a 1-chromacyclohexa-2,4-diene and subsequent reductive elimination to yield a cyclopentadiene **11-R²**. In

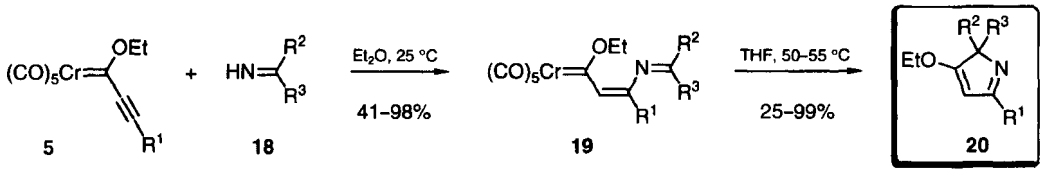
spite of being *trans*-configurated, complexes **7** upon heating in THF lose CO and give the chelate complexes **15**, which also react with alkynes to yield cyclopentadienes **11-R²**. Carbonyl insertion in the intermediate **17** is apparently slowed down by the strongly electron donating internal dialkylamino group. In fact, with a methoxy or phenylthio substituent instead of the dialkylamino substituent in the starting material of type **7**, the insertion of alkynes gave hydroquinone monoethyl ethers as products of a regular



Scheme 4. Mechanistic considerations for the formation of 5-amino-3-ethoxycyclopentadienes **11-R²**.

Dötz reaction followed by elimination of methanol or thiophenol (ref. 15). It turned out that the cyclopropyl substituent on the alkenyl terminus is also essential for the production of cyclopentadienes **11-R²** in high yield. With an isopropyl or an *n*-propyl instead of the cyclopropyl group the cyclopentadienes **11-R²** were formed in 14 and 9% yield only (ref. 14). So, it appeared that this valuable new synthesis of highly functionalized cyclopentadienes was limited to cyclopropyl-substituted complexes of type **6/7** and thereby drastically devoid of generality.

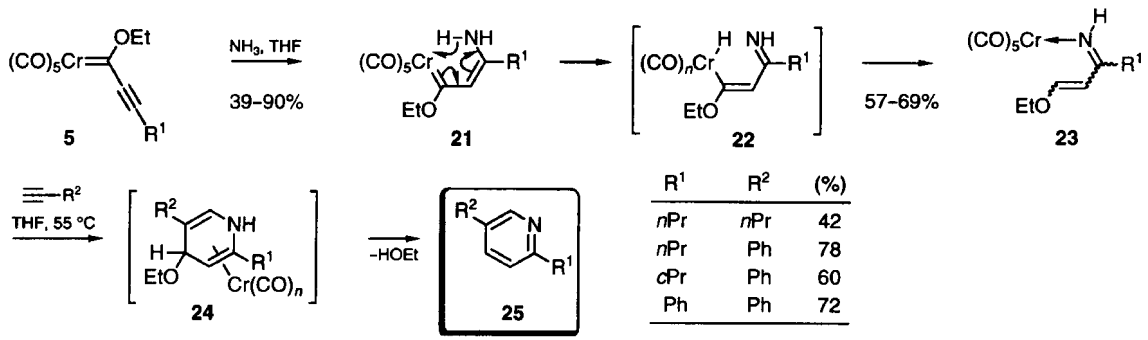
In view of this, the implications of the nature of various substitutents at the alkenyl terminus on the outcome of the reaction with alkynes were further examined. Ketimines **18**, which are known to 1,4-add only to highly reactive Michael acceptors (ref. 16), do react with complexes **5** and give the 1,4-adducts **19** in high yields (Scheme 5). These compounds do not incorporate alkynes, but even in the presence of alkynes rather cyclize to 2*H*-pyrroles **20**, as proved by an X-ray structure analysis of one of the examples (ref. 17). This reaction resembles the cyclization of 1-chroma-5-aza-1,3,5-trienes formed by insertion of an ynamine into a 1-imino-substituted carbenechromium complex, as previously observed by Aumann et al. (ref. 18). The 1-chroma-5-aza-1,3,5-triene **19** undergoes 6π-electrocyclization to a 1-chroma-4-azacyclohexa-2,4-diene, which subsequently reductively eliminates the carbonylchromium residue.



R¹	R²	R³	(%)	R¹	R²	R³	(%)
*n*Pr	Ph	Ph	88	*n*Pr	Ph	*c*Pr	88
*c*Pr	Ph	Ph	96	*c*Pr	Ph	*c*Pr	97
*t*Bu	Ph	Ph	99	*c*Pr	*c*Pr	*c*Pr	81
*n*Pr	*p*-MeOC$_6$H$_4$	*p*-MeOC$_6$H$_4$	57				

Scheme 5. 2*H*-Pyrroles **20** from 3-(Diorganylmethylenamino)alkenylidenechromium complexes **19**.

Complexes **21** with a primary amino group at the alkenyl terminus, easily obtained by addition of ammonia to alkynyl-substituted complexes **5**, first rearrange upon heating to pentacarbonylchromium-coordinated 1-aza-1,3-butadienes **23**, as proved by an X-ray structure analysis of one example (Scheme 6). These coordi-

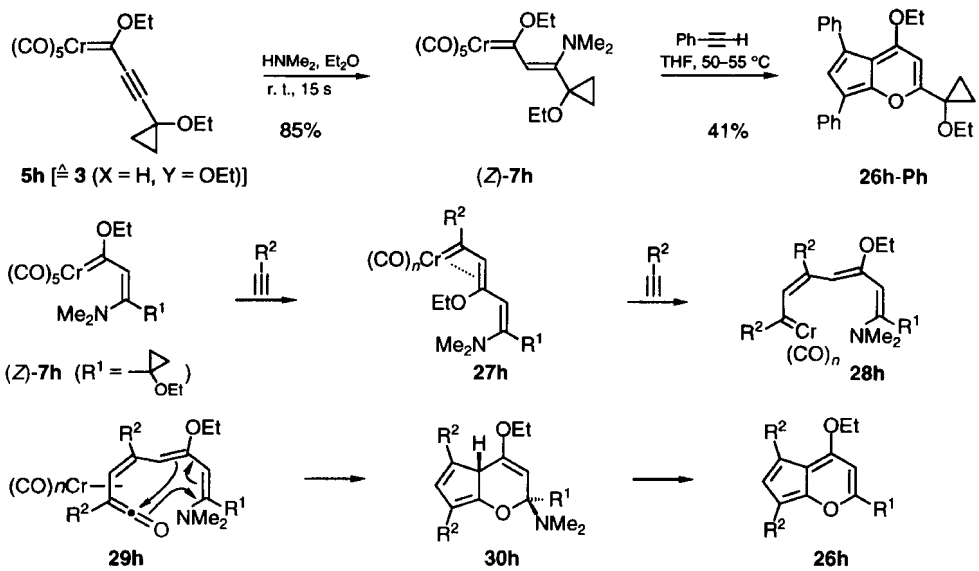


R^1	R^2	(%)
*n*Pr	*n*Pr	42
*n*Pr	Ph	78
*c*Pr	Ph	60
Ph	Ph	72

Scheme 6. Coordinated 1-aza-1,3-butadienes **23**: Stable intermediates in the formation of pyridines **25** from [(β-aminoethenyl)carbene]chromium complexes.

nated 1-aza-1,3-butadienes subsequently cycloadd alkynes in a [4+2] mode to give coordinated 4-ethoxy-1,4-dihydropyridines **24**, which 1,4-eliminate ethanol to yield substituted pyridines **25** (42–78%) (ref. 19).

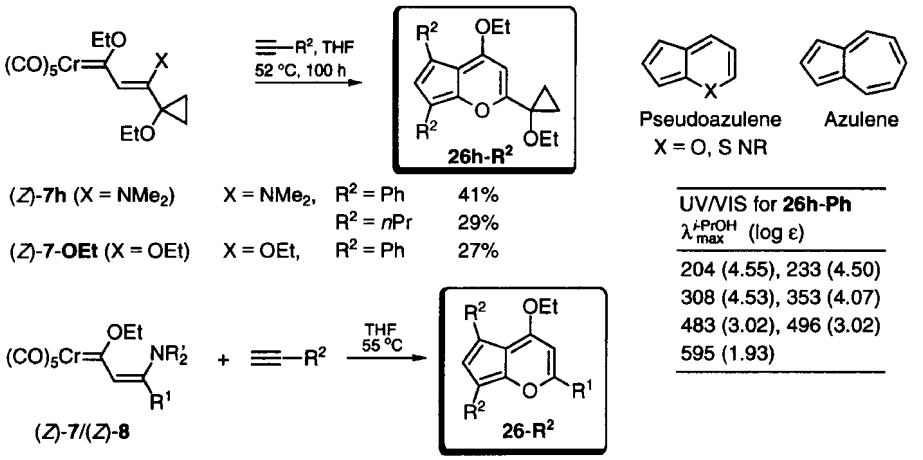
As both the dialkylamino and the cyclopropyl substituent had been found to be essential for the formation of highly substituted cyclopentadienes **11/12** in high yields, the next step was to modify the electronic properties of the cyclopropyl substituent itself. Therefore, the 1-ethoxycyclopropylethynyl-substituted complex **5h** was prepared from 1-ethoxyethynyl-1-cyclopropane by the standard procedure (ref. 11). Addition of dimethylamine proceeded as smoothly and rapidly as usual, but gave the (*Z*)-configurated complex (*Z*)-**7h**, as proved by nuclear Overhauser effect (NOE) measurements. This α,β-unsaturated β-amino-substituted complex (*Z*)-**7h** upon treatment with phenylacetylene gave another new product, which had never been observed before. An X-ray crystal structure analysis revealed this product to be the cyclopenta[*b*]pyran **26h-Ph** (Scheme 7).



Scheme 7. A cyclopenta[*b*]pyran **26h-Ph** from a 3-(1'-ethoxycyclopropyl)propylidene-carbene complex **5h**.

With the (*Z*)-configurated starting material (*Z*)-**7h** an alkyne insertion apparently gives an intermediate 1-chroma-1,3,5-hexatriene **27h** with a (*Z*)-configurated central double bond, which cannot 6π-electrocyclize. It rather inserts another alkyne to yield intermediate **28h**, which subsequently inserts a carbonyl group to a carbonylchromium complexed trienylketene **29h**. This intermediate can undergo an intramolecular [4+2] cycloaddition to give **30h**, which finally 1,4-eliminates dimethylamine to yield the observed product (ref. 20).

The same product was also formed from the β-ethoxy-substituted complex (*Z*)-**7h-OEt**, albeit in lower yield (Scheme 8). Such cyclopenta[*b*]pyrans contain a 10π-electron system and are thereby heterocyclic analogues of azulene. They and their thia and aza analogues have therefore rightly been termed pseudoazulenes, as revealed by their electronic absorption spectra. Two other methods for the preparation of such pseudoazulenes have been reported (refs. 21,22), but both give rather low yields and none of them could be used for cyclopenta[*b*]pyrans with the substitution pattern and substituent type as in **26h** (ref. 23).



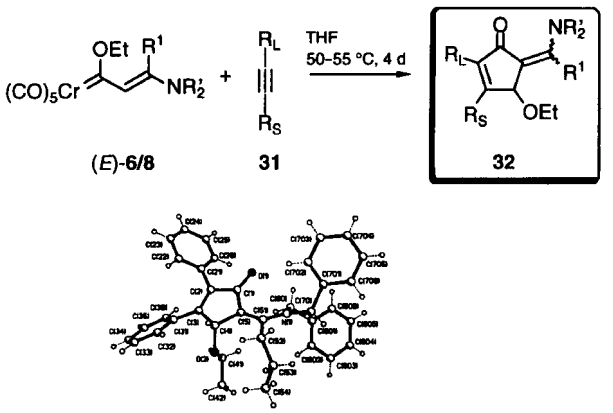
	R¹	NR'₂	R²	Product	(%)		R¹	NR'₂	R²	Product	(%)
(*Z*)-**8g**		NBn_2	C_6H_5	**26g-Ph**	68	(*Z*)-**7j**		NMe_2	C_6H_5	**26j-Ph**	84
(*Z*)-**7g**		NMe_2	*n*Pr	**26g-*n*Pr**	59				*n*Pr	**26j-*n*Pr**	5
(*Z*)-**8h**		NBn_2	C_6H_5	**26h-Ph**	47	(*Z*)-**7k**		NMe_2	C_6H_5	**26k-Ph**	57
(*Z*)-**7h**		NMe_2	*n*Pr	**26h-*n*Pr**	17						
(*Z*)-**7i**		NMe_2	C_6H_5	**26i-Ph**	90	(*Z*)-**8l**		NBn_2	C_6H_5	**26l-Ph**	74
			*n*Pr	**26i-*n*Pr**	21			NBn_2	*n*Pr	**26l-*n*Pr**	23

Scheme 8. An easy access to cyclopenta[*b*]pyrans (oxapseudoazulenes) **26-R²**.

For the formation of cyclopenta[*b*]pyrans, the presence of the ethoxycyclopropyl substituent was not essential. In fact, the corresponding (*Z*)-configurated complexes **7g**, **8g**, **7i** all gave even better yields of cyclopenta[*b*]pyrans **26-R²** than (*Z*)-**7h** (Scheme 8). In all cases, phenylacetylene was incorporated with consistently higher yields than 1-pentyne. In addition, yields were always slightly better with a dibenzylamino leaving group. The cycloadduct **26k-Ph** with a dioxolane moiety could be deprotected to the acetyl-substituted cyclopenta[*b*]pyran. The double insertion-cycloaddition also worked well with the bulky secondary substituent in (*Z*)-**8l**. And not even the (*Z*)-configuration of the starting material was essential, as the 3-(dibenzylamino)-3-phenylpropenylidene complex **8f** and its dimethylamino analogue **7f**, which according to NOE measurements are (*E*)-configurated, reacted with phenylacetylene to give the correspondingly substituted cyclopenta[*b*]pyrans in 48 and 24% yield, respectively (ref. 23). In the reaction of complex (*Z*)-**7i** with 1-pentyne, a fulvenetricarbonylchromium complex was formed as the major product (38%) (ref. 24).

A WEALTH OF PRODUCTS WITH THE APPROPRIATE VARIATION OF CONDITIONS

The formation of cyclopentadienes as well as cyclopenta[*b*]pyrans from 3-dialkylamino-substituted alkenylidene complexes were only observed with terminal alkynes. Complexes (*E*)-**6/8** reacted with disubstituted acetylenes **31** in yet another mode. In refluxing tetrahydrofuran (THF), 5-(dibenzylamino-methylene)cyclopent-2-enones **32** were formed in good yields (Scheme 9). The structural assignment again rests on an X-ray crystal structure analysis (ref. 25).

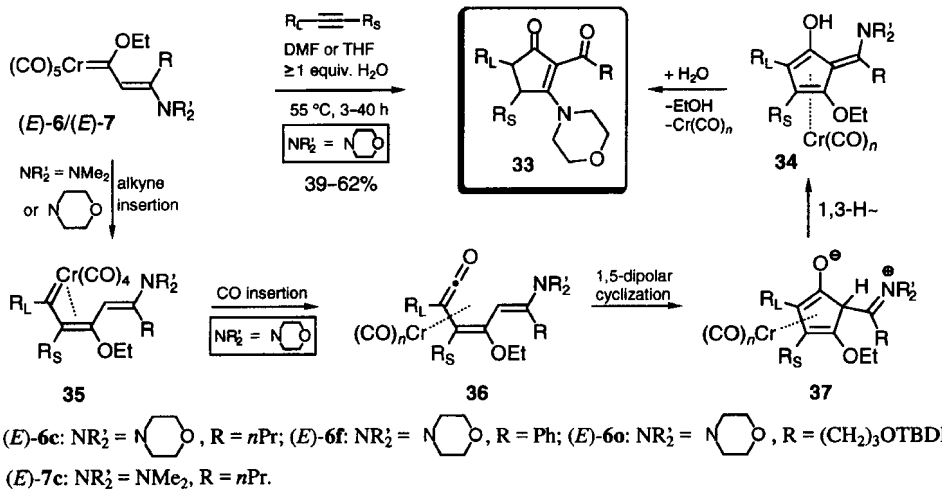


R^1	NR^1_2	R_L	R_S	Yield (%)	*Z*-Isomer (%)[a]	
*n*Pr	NBn_2	Ph	Ph	68	75	
*n*Pr	NBn_2	Me	Me	78	64	
*n*Pr	NBn_2	$-(CH_2)_6-$		75	67	
*c*Pr	NBn_2	Ph	Ph	59	>95	
*c*Pr	NBn_2	$-(CH_2)_6-$		62	90	
*n*Pr		*n*Pr	H	66	69	[b]
		*n*Pr	H	62	69	[b]

[a] In $CDCl_3$, solvent dependent. - [b] 0.05 M in complex, 0.15 M alkyne in DME, 80 °C, 6 h.

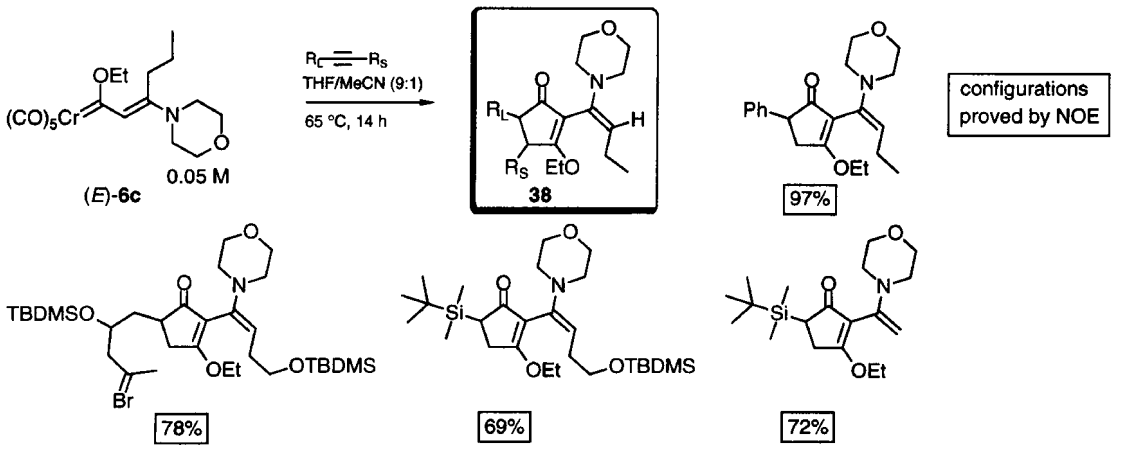
Scheme 9. 5-Methylenecyclopent-2-enones **32** as new formal [2+2+1] cycloadducts from [2-(dibenzylamino)ethenyl]carbenechromium complexes (*E*)-**6/8** and internal alkynes.

When performed in THF containing one equivalent of water (or in moist DMF), the same reaction yielded 2-acyl-3-morpholinylcyclopent-2-enones **33** (Scheme 10). Both these transformations apparently occur with carbonyl insertion. Complexes (*E*)-**6**/(*E*)-**7** after the usual alkyne insertion, must insert CO to yield the 4-dialkylaminobutadienylketene complexes **36**, the same type of intermediates which occur in the Dötz reaction (ref. 2). With the dialkylamino substituent, however, complexes **36** apparently are more highly polarized and therefore do not undergo the typical 6π-electrocyclization, but rather a 1,5-dipolar cyclization to yield cyclopentadienyl intermediates of type **37**, and a subsequent 1,3-proton shift to give **34**. In the absence of water, these can tautomerize with loss of the carbonylchromium fragment to yield compounds **32** (Scheme 9), but in the presence of water, the enamine moiety is hydrolyzed to an acyl group, yet the secondary amine readds to the α,β-double bond in the 3-ethoxycyclopent-2-enone with subsequent elimination of ethanol to give compounds **33** (Scheme 10) (ref. 26).



Scheme 10. 2-Acyl-3-morpholinylcyclopent-2-enones **33** from 3-morpholinylalkenylidene complexes (*E*)-**6**.

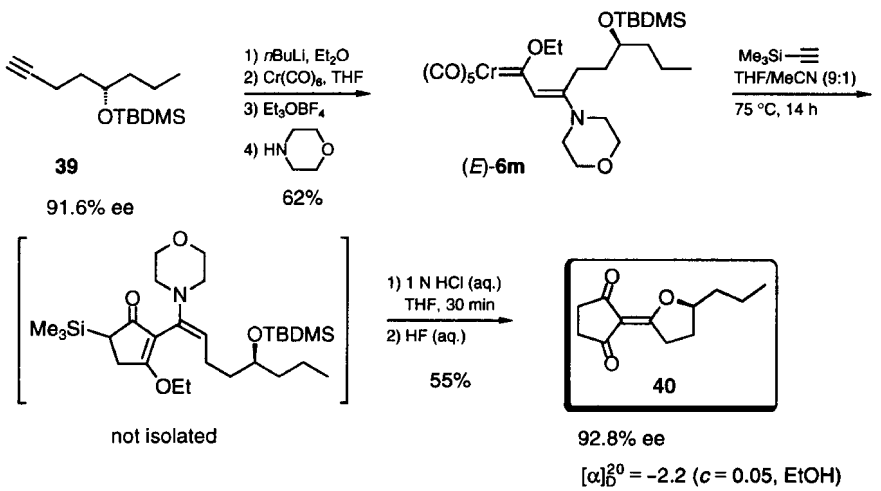
When this very same reaction was performed with a complex of type (*E*)-**6c** in a mixture of THF and acetonitrile (MeCN) (9:1) at 65 °C, 2-(1'-morpholinyl-1'-alkenyl)-3-ethoxycyclopent-2-enones **38** were obtained, apparently formed via the same intermediate **34** by 1,5-proton migration from the alkyl position next to the aminocarbenium/immonium ion moiety to the carbon atom bearing R_S. This reaction, obviously, can only proceed with complexes (*E*)-**6**, which do contain at least one allylic proton in the alkenylidene ligand, and best yields were observed with a morpholinyl group attached (Scheme 11). Products **38** do hydrolyze to **33** when subjected to chromatography on silica gel, but can be purified by chromatography on silylated alumina (ref. 27).



Scheme 11. 2-(1'-Morpholinyl-1'-alkenyl)-3-ethoxycyclopent-2-enones **38** from 3-morpholinyl-2,3-unsaturated carbenechromium complexes (*E*)-**6**.

The reaction conditions are compatible with a number of functionalities both in the alkyl side-chain of the starting materials (*E*)-**6** and the added alkyne, as some of the specified examples demonstrate (Scheme 11).

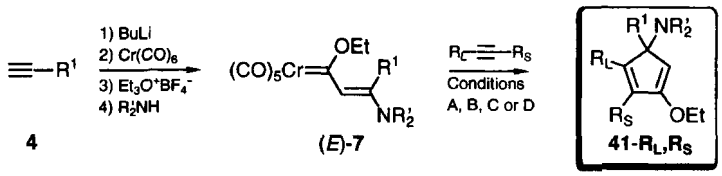
The ready accessibility of such protected 2-acyl-1,3-cyclopentanediones **38** led to a new short synthesis of (*S*)-oudenone (ref. 28), a tyrosine hydroxylase inhibitor. The starting material, complex (*E*)-**6m** was assembled in 62% yield from the chiral non-racemic alkyne **39**. Treatment with trimethylsilylacetylene in THF/MeCN (9:1) led to a product of type **38**, which was not isolated, but immediately treated with 1 N hydrochloric acid in THF and subsequently with aqueous hydrogen fluoride (Scheme 12). The target molecule **40** was obtained with practically the same enantiomeric purity (92.8% *e. e.*) as the starting material **39** used (ref. 27). This establishes the first enantioselective synthesis of (*S*)-oudenone, and it virtually proceeds in only two steps, since, as with other β-dialkylamino-substituted complexes of type **6/7/8**, the precursor (*E*)-**6m** was prepared in a one-pot operation (ref. 29).



Scheme 12. A short synthesis of (*S*)-(–)-oudenone **40**, a tyrosine hydroxylase inhibitor.

A NEW GENERAL SYNTHESIS OF 5-DIALKYLAMINO-3-ETHOXYCYCLOPENTADIENES

An extensive study of the effects of solvent, reagent concentrations, ligand additives and substituents on the product distribution obtained from β-amino-substituted α,β-unsaturated carbenechromium complexes revealed that the yields of 5-cyclopropyl-substituted cyclopentadienes of type **11/12** could be substantially increased to over 90%, when the complexes **6a/7a** were reacted in *n*-hexane at 55 °C. The real breakthrough, however, was achieved by running the reaction in pyridine as a solvent at 55 to 80 °C or in acetonitrile as a donor solvent at 80 °C with slow addition of the alkyne (syringe pump). Under these



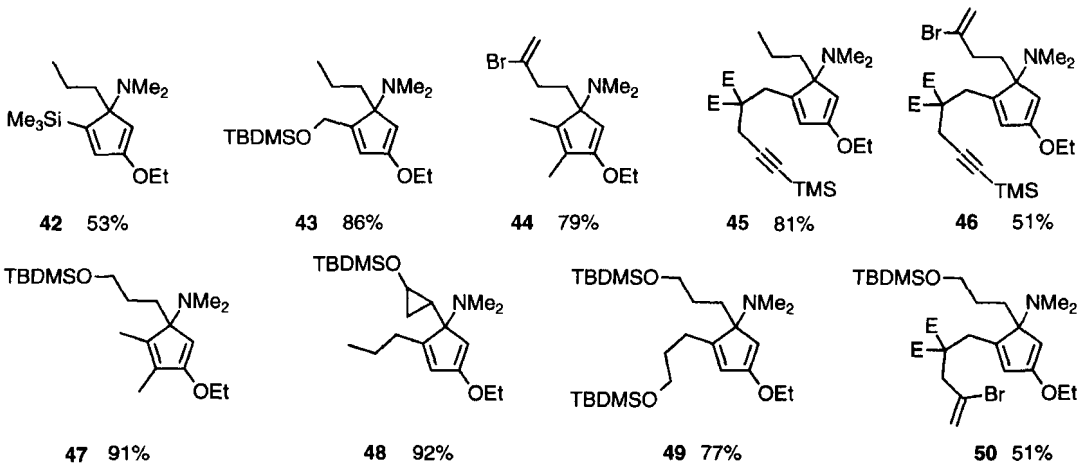
4 (*E*)-7 **41-R_L,R_S**

7	Complex R^1	R^1_2	Alkyne R_L	R_S	Conditions	Product	Yield (%)
a	*c*Pr	Me_2	*c*Pr	H	A	**41a**-*c*Pr	95
n		Me_2	*n*Pr	H	A	**41n**-*n*Pr	92
c	*n*Pr	Me_2	Me	Me	B	**41c**-Me,Me	95
c	*n*Pr	Me_2	Et	Et	B	**41c**-Et,Et	86
c	*n*Pr	Me_2	Ph	Ph	B	**41c**-Ph,Ph	80
c	*n*Pr	$-(CH_2)_4-$	Ph	H	C	**41c**-Ph	95
c	*n*Pr	Me_2	*t*Bu	H	C	**41c**-*t*Bu	73
o	$-(CH_2)_3OSiR_3$	Me_2	$-(CH_2)_3OSiR_3$	H	D	**41o**-$(CH_2)_3OSiR_3$	77

A: *n*-Hexane, 55 °C. - B: Pyridine, 55 °C. - C: MeCN, 80 °C, slow addition of alkyne. - D: Pyridine, 80 °C.

Scheme 13. A new general synthesis of highly substituted 5-(dialkylamino)-3-ethoxycyclopentadienes **41-R_L,R_S** (ref. 29).

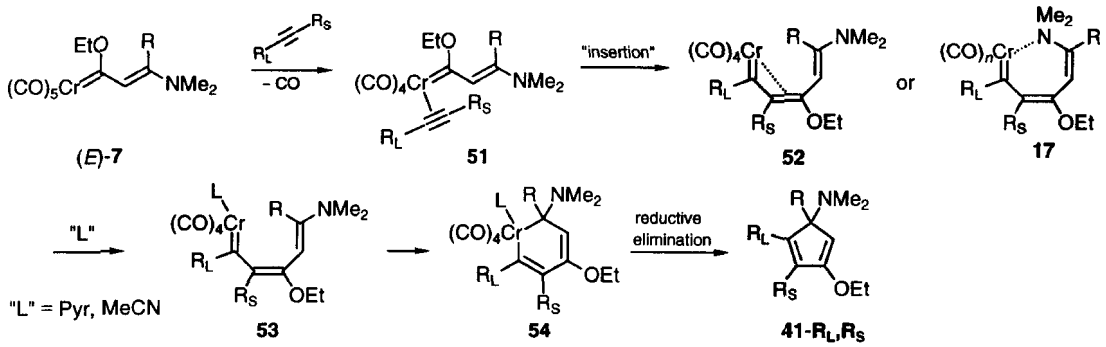
conditions, a great number of differently substituted complexes (*E*)-**7** (and analogues with a pyrrolidinyl group) and differently substituted alkynes gave the correspondingly substituted 5-dialkylamino-3-ethoxy-cyclopentadienes **41** in good to very good yields (Scheme 13).



The reaction conditions applied both for the formation of the starting materials (*E*)-**7** (and analogues) in a one-pot operation as well as the [3+2] cycloaddition of the alkyne are compatible with a variety of functionalities, as demonstrated by the examples **42**–**50** (ref. 29). This two-step synthesis of highly functionalized five-membered rings nicely complements existing methodology for the preparation of cyclopentenones, especially the Pauson-Khand reaction (ref. 30). The current new method appears to even go beyond the scope and limitations of other procedures.

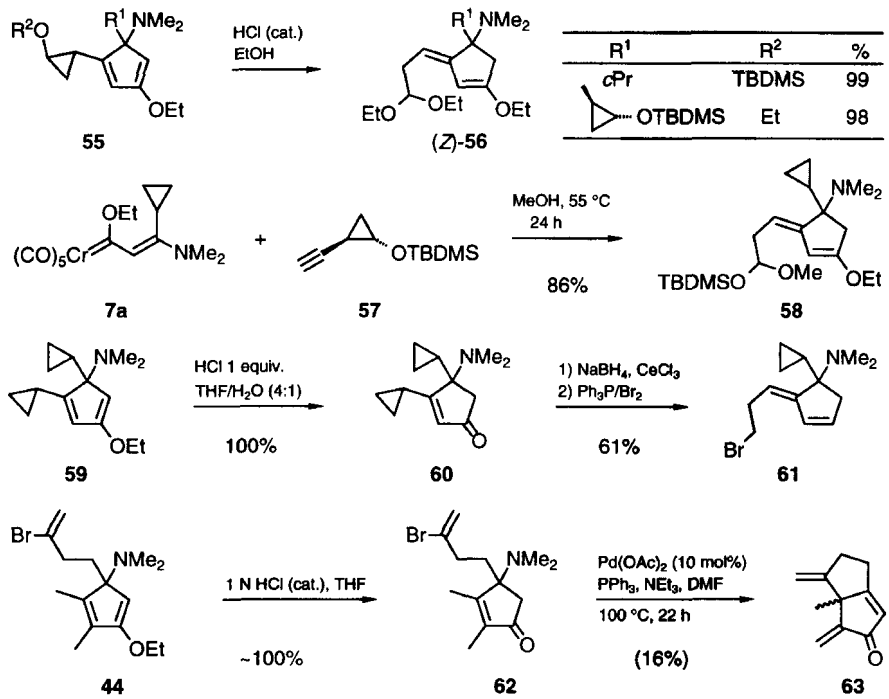
The mechanism of this formation of 5-dialkylaminocyclopentadienes can be rationalized in terms of a sequence of events, in which the first two steps, namely carbonyl to alkyne ligand exchange from (*E*)-**7** to **51** and subsequent insertion of the ligated alkyne to give a 1-chromahexa-1,3,5-triene **52**, would be identical to those in the well-known Dötz reaction (ref. 2). With the dialkylamino group at the alkenyl terminus, the starting material can isomerize to a chelate complex of type **15** (see above, Scheme 4), which would yield a chelated 1-chromahexatriene **17**. In the absence of a cyclopropyl group at the terminus, however, it is obvious that a donor solvent like pyridine or acetonitrile must be used to achieve good yields. Such solvent molecules would probably act as auxiliary ligands on the coordinatively unsaturated complexes of type **52** to give **53**, which then undergoes 6π-electrocyclization faster than CO insertion. This

is different from the sequence of events in the Dötz reaction and yields a 1-chromacyclohexa-2,4-diene **54** which by reductive elimination gives 5-dialkylaminocyclopentadienes **41-R_L,R_S** (Scheme 14, ref. 31).



Scheme 14. Mechanism of the formation of 5-(dialkylamino)-3-ethoxycyclopentadienes **41-R_L,R_S** from complexes (*E*)-**7** and analogues.

The virtue of such cyclopentadienes with a number of functional groups attached is outlined by a few examples. The oxycyclopropyl-substituted compounds **55**, when treated with a catalytic amount of hydrochloric acid in ethanol, are smoothly converted to purely (*Z*)-configurated 3-alkylidenecyclopent-1-enyl ethers (*Z*)-**56** in quantitative yields (Scheme 15). This transformation corresponds to a rarely observed 1,7-addition of ethanol to **54**. When the [3+2] cycloaddition of complex **7a** and alkyne **57** was performed in methanol instead of THF at 55 °C, the (*Z*)-configurated compound **58**, a mixed acetal analogue of (*Z*)-**56** was formed in 86% yield. Similarly, ring-opening of a cyclopropyl group without an oxygen substituent can be achieved by first reducing the hydrolysis product of **59**, the cyclopentenone **60**, to the corresponding allyl alcohol and subsequently treating this with the Ph_3P/Br_2 reagent (ref. 32). Another possible use is exemplified by a transformation of cyclopentadiene **44** with a 3'-bromobutenyl side chain. Treatment of **44** with hydrochloric acid yields cyclopentenone **62** quantitatively which, by an intramolecular Heck reaction, is converted to the dimethylenebicyclooctenone **63**. The yield of 16% in this first attempt definitely needs optimization (ref. 33).

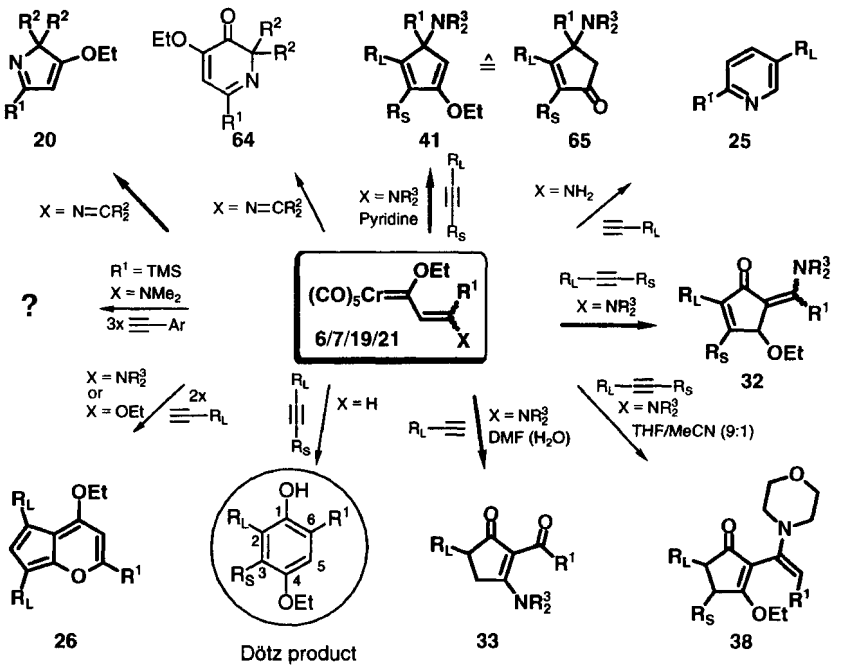


Scheme 15. Useful transformations of cyclopropyl and other functionally substituted 5-dialkylamino-3-ethoxycyclopentadienes.

CONCLUSION

Undoubtedly, β-dialkylamino-substituted α,β-unsaturated Fischer carbenechromium complexes are multitalented building blocks (Scheme 16). 3-(Diorganylmethylenamino)-substituted complexes **19** cyclize even in the absence of alkynes – only in one case was a 3-pyridone derivative **64** obtained, resulting from addition of an alkyne (ref. 17). The [3+2] cycloadditions of alkynes to complexes **6/7** without carbonyl insertion can be brought about selectively in pyridine or acetonitrile solutions. Complexes **21** with a primary amino group first rearrange and then cycloadd to yield pyridines **25** (ref. 19). Especially with a morpholinyl group as in **6**, dialkylamino-substituted complexes add internal as well as terminal alkynes with carbonyl insertion to selectively give – each under a specific set of conditions – either 5-(1'-dialkylaminoalkylidene)cyclopent-2-enones **32** or (ref. 25) 3-ethoxy-1-(1'-morpholinyl-1'-alkenyl)cyclopent-2-enones **38** (ref. 27) or 2-acyl-3-dialkylaminocyclopent-2-enones **33** (ref. 26). With extremely bulky groups R^1 at the alkenyl terminus, complexes **6/7/8** are (*Z*)- rather than (*E*)-configurated and prefer to insert two molecules of the alkyne and CO to finally yield cyclopenta[*b*]pyrans **26**. Even a three-fold insertion of alkynes without CO insertion was observed for complexes **6/7** containing a trimethylsilyl substituent in the place of R^1, yet the structure of this product remains elusive (refs. 15,31).

The ready accessibility of 5-dialkylamino-3-ethoxycyclopentadienes **41-R_L,R_S** is particularly noteworthy (ref. 29). These compounds are enol ethers of cyclopentenones and can also be regarded as protected cyclopentadienones (or precursors thereof), which are in a sense template assembled from two molecules of an alkyne and carbon monoxide stemming from hexacarbonylchromium. This is analogous to the Dötz reaction, a template-assisted assembly of an alkyne, two carbon monoxide and an alkene molecule.



Scheme 16. The variability of products from β-amino substituted α,β-unsaturated carbenechromium complexes and alkynes under different conditions.

Eventually, 5,5-disubstituted cyclopentadienes of type **41** may be accessible in enantiomerically pure form along this new route using a chiral amine auxiliary in the starting materials of type **6/7/8**. In fact, diastereomeric selectivities (d. s.) of up to 89% have already been achieved in first trials with a (2-methoxymethyl)pyrrolidinyl group as an auxiliary (ref. 35).

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