Recent Developments in the Synthetic Uses of Chlorosulfonyl Isocyanate

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Contents

I. Introduction

Chlorosulfonyl isocyanate (CSI), the most reactive isocyanate known, was discovered by Graf in 1952. Reviews[1-3] on the chemistry of this remarkable electrophile have appeared which cover the literature through 1968. The purpose of this paper is to review the recent advances in both the synthetic and the mechanistic applications of CSI.

If one conceives of $ClSO_2N{=}C{=}O$ as an electrophile, one can visualize two points of attack by nucleophilic reagents: at the SO_2 group and at the C=O function. Furthermore, cycloadditions to the C=N of the cumulative function (isocyanate) can occur. Although the above-mentioned criteria appear attractive for classification of reaction types, often the isolated products are not necessarily those initially formed. Hence the reactions of CSI were originally classified by Graf into three main groups based on final product.[2] We will maintain essentially the same classifications, with some modifications, and would like to emphasize the fact that these groups are distinguished by differences in product type which sometimes, but not always, coincide with actual reaction mechanisms.

Reactions of type I usually involve the addition of the elements of H–X (or Y–X), where X is a nitrogen, oxygen, or sulfur nucleophilic species, to the isocyanate function of CSI, resulting in the formation of compounds such as **1.** A few examples include cases involving Y–X reagents, where Y is other than hydrogen.

Reaction type II will treat reactions that result in attachment of carbon groups to the C=O function of CSI, including all cycloadditions of CSI to multiple bonds which lead predominantly to lactams. Reactions involving the chlorosulfonyl group are classified as belonging to type III.

The physical properties of CSI, as well as techniques for its handling and storage, were noted previously.[2] Detailed infrared and Raman spectra of CSI have now been reported.[4]

II. Reactions of Type I. Simple Additions to the Isocyanate Function

These reactions involve chiefly attachment (nucleophilic attack) of N, S, and O functions to the carbonyl group of CSI.

A. Reactive Hydrogen Compounds

As would be expected of an isocyanate, CSI reacts with alcohols (or thiols) and amines to yield carbamate and urea derivatives **1**, respectively (X = OR, SR, or NR_2). These derivatives, **1**, still substituted with the reactive *N*-chlorosulfonyl group, undergo a variety of further transformations.[2] A few examples (previously reviewed)[2] are shown in eq 2 and 3.

$$ClSO_2N{=}C{=}O + H{-}X \longrightarrow ClSO_2NHC(=O)X \quad (1)$$

1

X = O, S, or N function

$$ROH + CSI \longrightarrow R{-}O{-}C(=O){-}NHSO_2Cl \xrightarrow{H_2O} R{-}O{-}C(=O){-}NH_2 \quad (2)$$

R = C_2H_5, $ClCH_2CH_2$–, $(CH_3)_2CH$–, Ph, $PhCH_2$, *p*-ClC_6H_4–, c-C_6H_{11}–

$$R_2NH + CSI \longrightarrow R_2NC(=O)NHSO_2NR_2 \quad (3)$$

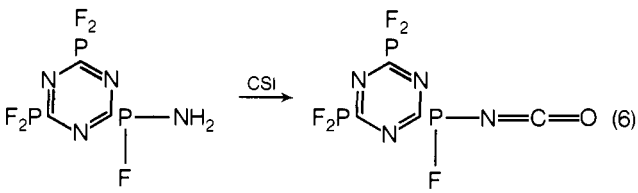
R = CH_3, C_2H_5

Because of its high reactivity, CSI also undergoes type I reactions with amides and sulfonamides. The addition products of sulfonamides (**1a**) can be readily converted into sulfonyl isocyanates **2** via pyrolytic elimination of sulfamoyl chloride.[5,6] For R = perfluoroalkyl, i.e., R_f = CF_3, C_4F_9, C_8F_{17}, yields of **2** range from 75 to 92%,[5] while for R = alkyl or aryl, **2**, i.e., R = C_6H_5, *p*-$CH_3C_6H_4$, CH_3, is produced in 18 to 30% yield[6] and often intermediate **1a** need not be isolated. Whether in the latter cases products of type III arise has not been determined. It has been shown, however, that N-substituted sulfonamides react at the chlorosulfonyl group of CSI (see section IV.D). Results analogous to those found in sulfonamides have been reported for the reaction of perfluoroalkanesulfinamides **3** with CSI to furnish sulfinyl isocyanates **4**.[6b]

$$R_fS(O)NH_2 \;(\mathbf{3}) + CSI \xrightarrow[2.\,100\,^\circ C]{1.\,-80\,^\circ C} R_fS(O)NCO \;(\mathbf{4}) \quad (92\text{–}95\%) \qquad (5)$$

$R_f = CF_3, n\text{-}C_4F_9$

Even certain phosphoramides have been converted to isocyanates.[7]



(6)

CSI also reacts readily with carboxylic acids. The initial adducts are unstable and lose carbon dioxide to produce a *N*-chlorosulfonylcarboxamide **5**,[2] which can be readily converted into nitriles **6** by treatment with dimethylformamide (DMF)[2] or with triethylamine (eq 7).[3] An analogous reaction to that

$$RCOOH + CSI \longrightarrow RCOOCONHSO_2Cl \xrightarrow{-CO_2} RCONHSO_2Cl \;(\mathbf{5}) \longrightarrow RCN\;(\mathbf{6}) + SO_3 + HCl \qquad (7)$$

R = c-C_6H_{11}–, $ClCH_2CH_2$–, $CH_3CH{=}CHCH{=}CH$–, $PhCH_2$–, $PhCH{=}CH$–, $EtOOCCH_2CH_2$–, $-(CH_2)_8-$

with carboxylic acids has been reported with betaines **7.** The final products **8** were isolated by conversion to the ethyl esters **9**[8] (Scheme I). Reaction of CSI with *tert*-butyl hydroperoxide at low temperature gives the unstable adduct **10** which can be transformed into more stable adducts by subsequent reaction of the SO_2Cl group with other nucleophiles[9a] (Scheme II).

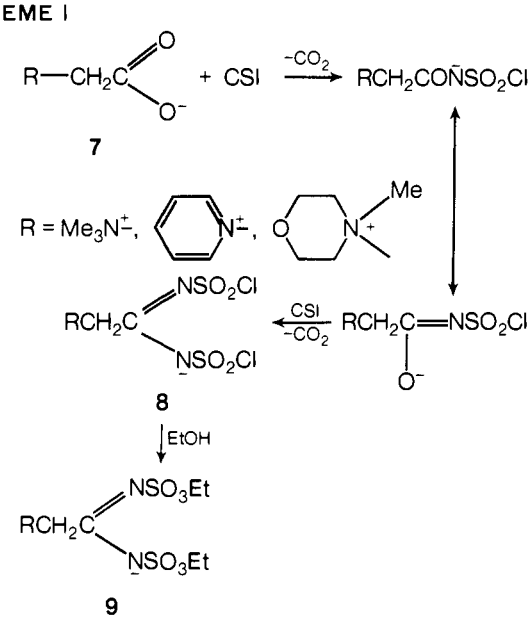
An interesting synthesis of amines from alcohols has recently been described.[9b] This applies mainly to tertiary or benzylic alcohols ROH in which the alkyl portion R is able to support a positive charge well (Scheme III).

Industrially, type I reactions have been used in the solubilization of disperse dyes,[10a] and in the crosslinking of cellulose to produce derivatives which could be used as ion-exchange resins.[10b]

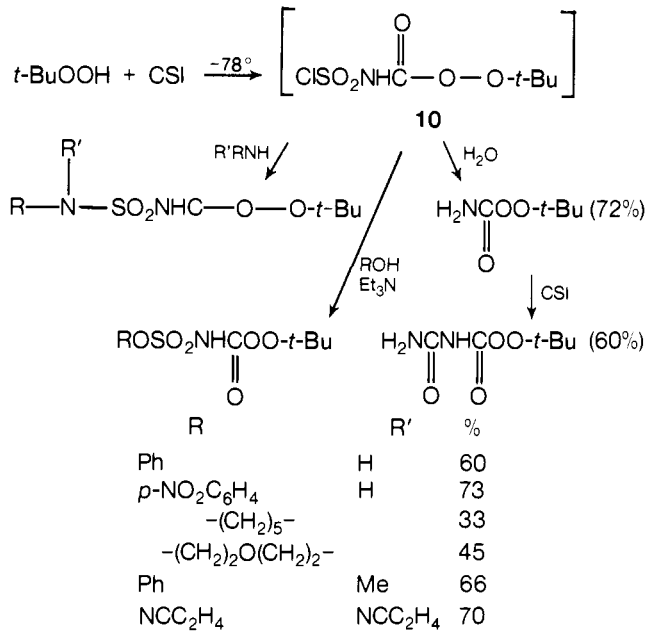
B. Acetals

Methylal **12** was previously reported to undergo a type I reaction with CSI, producing **13**.[2] The reaction probably takes

SCHEME I



SCHEME II



R	R′	%
Ph	H	60
p-$NO_2C_6H_4$	H	73
$-(CH_2)_5-$		33
$-(CH_2)_2O(CH_2)_2-$		45
Ph	Me	66
NCC_2H_4	NCC_2H_4	70

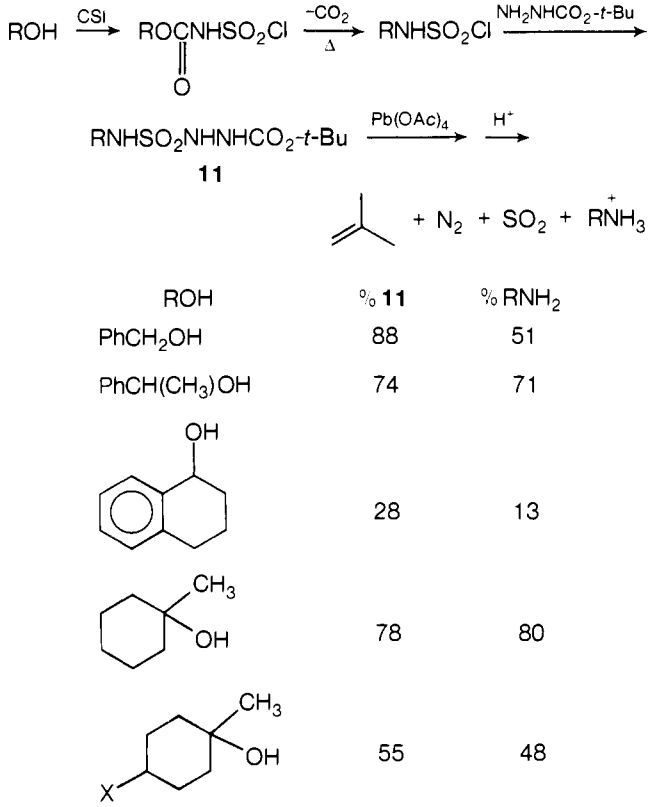
the course shown in Scheme IV and appears to be a general reaction of acetals of aliphatic aldehydes.[11] For example, *s*-trioxane **15** and 1,3,5,7-tetroxocane **14a** both produce the cyclic carbamate **16**, whereas metaldehyde **14b** leads only to **17.** These transformations have been explained by the series of additions and eliminations shown in Scheme V.[11] Ortho esters behave similarly with CSI.[2]

The reaction of ketones and aldehydes with CSI sometimes leads to products in which oxygen is attached to the C=O of the isocyanate, but for the sake of unity all reactions of aldehydes and ketones are treated in section III.

III. Reactions of Type II. Cycloadditions and Reactions with Carbon Multiple Bonds

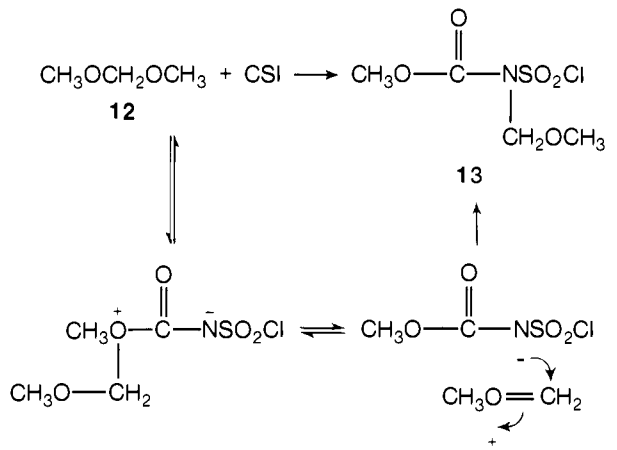
Chlorosulfonyl isocyanate undergoes cycloaddition to a variety of multiple bonds.[1-3] With olefins (2 + 2) cycloadducts can often be isolated. With aldehydes and many ketones the reaction is more complicated. Though the reaction may proceed by initial attack of the carbonyl O on the isocyanate carbon, the isolated products have widely different structures depending upon the substrates used.

SCHEME III



ROH	% 11	% RNH_2
$PhCH_2OH$	88	51
$PhCH(CH_3)OH$	74	71
	28	13
	78	80
	55	48

SCHEME IV

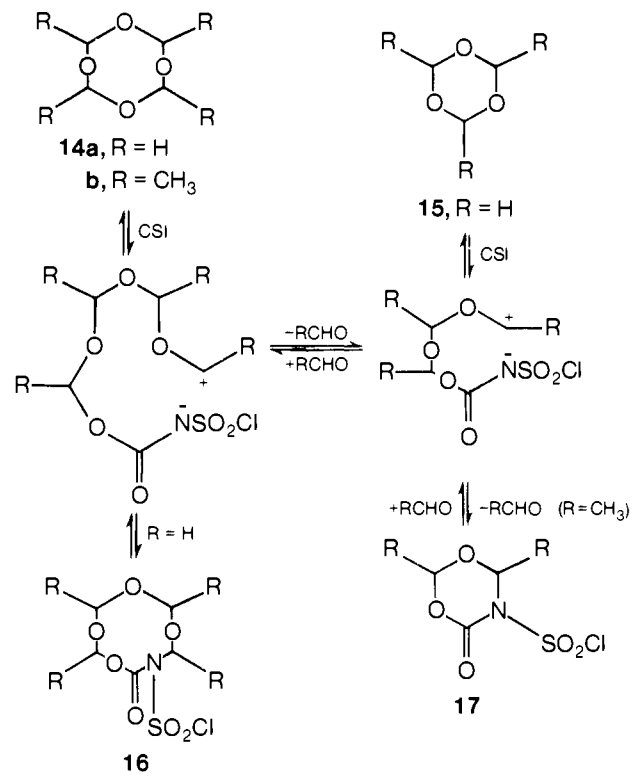


A. Aldehydes

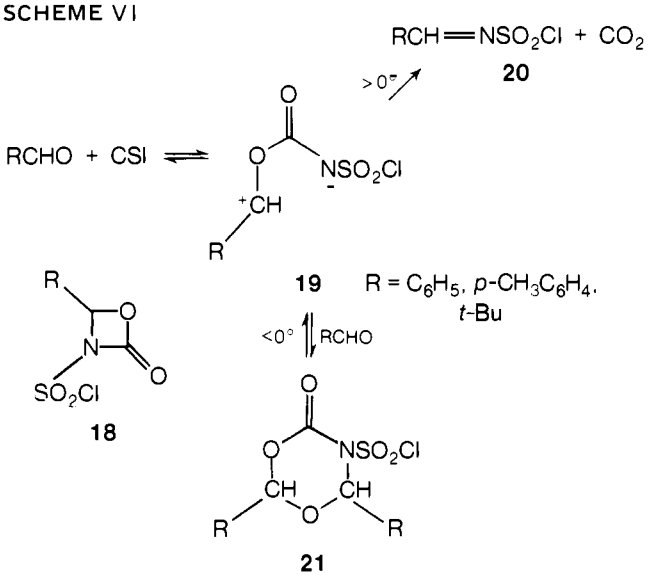
Aldehydes behave differently from most ketones and produce azomethine-*N*-sulfonyl chlorides **20** and carbon dioxide. A reversible by-product which can be isolated at low temperature is the dioxazinone **21** (type I product). Similar results are observed with fluorosulfonyl isocyanate (FSI).[11] The intermediate in the formation of **20** was originally thought to be the oxazetidinone **18** derived from (2 + 2) cycloaddition.[2] Recently, Clauss, Friedrich, and Jensen have favored the intermediacy of the 1,4-dipole **19**.[11] However, the exact timing of C–N bond formation in relation to CO_2 elimination is difficult to determine and, therefore, the transient formation of the oxazetidinone **18** should not be entirely discounted (see Scheme VI).

The complete absence of enol-derived products (see section III.B.1) in these reactions is somewhat surprising. In fact, aldehydes with enolizable hydrogens were observed, in the presence of CSI or FSI, to rapidly trimerize to acetals **15**, which then reacted as previously described. No explanation for this result was offered.[11]

SCHEME V



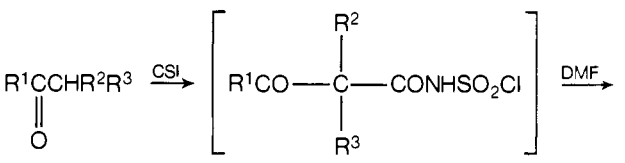
SCHEME VI

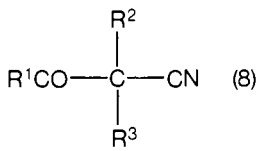


B. Ketones

1. Simple Ketones

CSI undergoes electrophilic addition to enolizable ketones **22**, producing *N*-chlorosulfonyl-β-ketocarboxamides **23**.[11,12]





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SCHEME VII

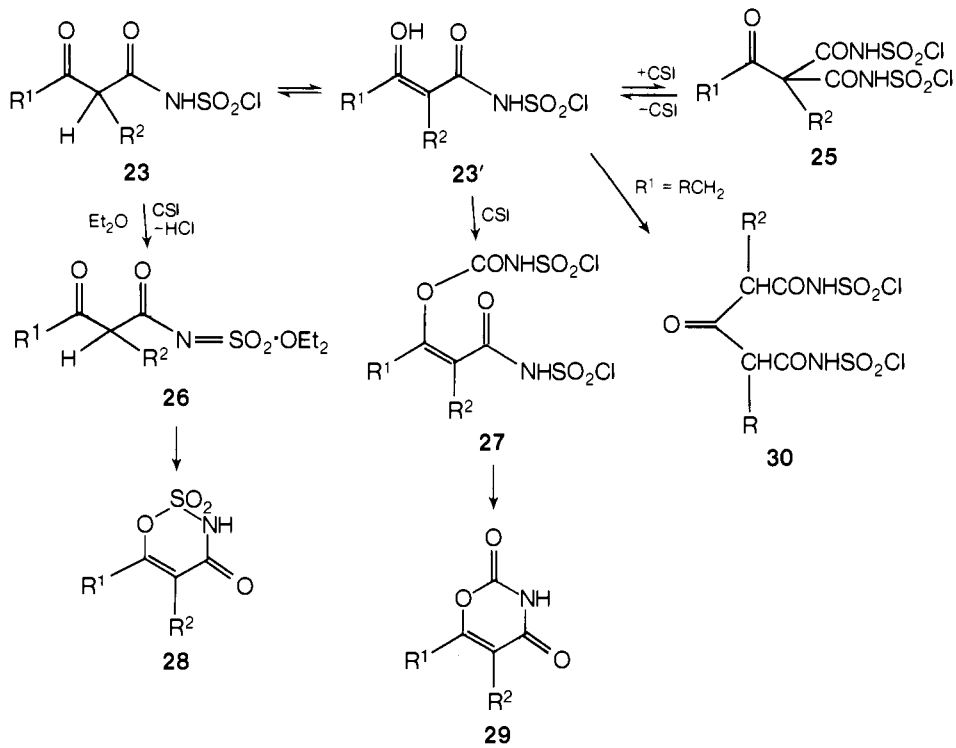


TABLE I. β-Ketonitriles 24 from Ketones 22

R^1	R^2	R^3	% yield
C_6H_5	CH_3	H	90
C_6H_5	C_2H_5	H	82
C_6H_5	CH_3	CH_3	80
C_2H_5	CH_3	H	71
CH_3	CH_3	CH_3	87
CH_3	CH_3	H	63
CH_3	$COCH_3$	H	70
$-(CH_2)_3-$		H	54
$-(CH_2)_4-$		H	69

In almost all cases reported, amides **23** are not isolated, but can serve as valuable intermediates in the synthesis of a number of important compounds. Thus, treatment with DMF provides a new, general one-pot synthesis of β-ketonitriles **24** (Table I).[13] In the presence of excess CSI, further transformations of amide **23** (R^3 = H) are observed, with the final product distribution being quite sensitive to the effects of solvent, substituents and concentration.[12,14,15]

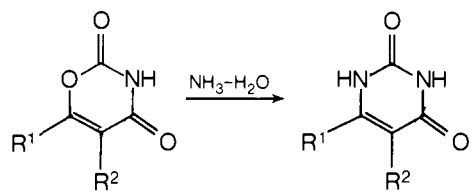
One of the further transformations that β-ketoamides can undergo involves a second electrophilic addition of CSI to the enol **23'** to produce a malonamide derivative **25.** This generally occurs with aliphatic ketones in dichloromethane solution,[15] or with aromatic ketones under appropriate conditions[14] (Table II). With certain aliphatic ketones, α,α'-diamides **30** are produced rather than malonamides **25.** In solution, the malonamide **25** readily eliminates CSI to regenerate β-ketoamide **23** (see Scheme VII).

In ether solvent and providing that R^1 = aryl, CSI acts as a Lewis acid in promoting the cyclization of **23** to 1,2,3-oxathiazin-4-(3*H*)-one 2,2-dioxide derivatives **28** (Table II). The *N*-sulfonyl amine **26** is believed to be an intermediate.[14] Oxathiazinone dioxides **28,** some of which show potential as sweetening agents, have also been produced from *N*-fluorosulfonyl-β-ketocarboxamides by treatment with base.[16] Alternatively, CSI can react in a type I reaction with enol **23'** to produce enol carbamate **27.** Cyclization with loss of sulfamoyl chloride, followed by hydrolytic workup, provides 2*H*-1,3-oxazine-2,4(3*H*)-diones **29** in fair yields (Table II). The fact that **29** is produced from both aliphatic and aromatic ketones is of prime importance since **29** can be converted in nearly

TABLE II. Product Distribution from Ketones 22 (R_3 = H) and CSI

R^1	R^2	Solvent	% 25	% 28	% 29
C_6H_5	CH_3	Ether		42	28
		CH_2Cl_2			43
		CH_2Cl_2	62[a]		
C_6H_5	C_2H_5	Ether		41	8
		CH_2Cl_2			46
CH_3	C_6H_5	Ether			71
$C_6H_5CH_2$	C_6H	Ether			61
C_6H_5	C_6H_5	Ether		28	14
$-o-C_6H_4(CH_2)_2-$		Ether		20	30
		CH_2Cl_2	22[a]		
C_6H_5	C_6H_5CO	Ether or CH_2Cl_2			10
$p-CH_3OC_6H_4$	CH_3	Ether		3	
$p-CH_3C_6H_4$	CH_3	Ether		30	3
$p-ClC_6H_4$	CH_3	Ether		21	13
C_2H_5	CH_3	CCl_4	77		
C_3H_7	C_2H_5	CH_2Cl_2	71		2
$i-C_4H_9$	$i-C_3H_7$	CH_2Cl_2			24
$-(CH_2)_3-$		CCl_4	87		
$-(CH_2)_4-$		CH_2Cl_2	61		31
$-(CH_2)_5-$		CH_2Cl_2			61
$-(CH_2)_6-$		CH_2Cl_2			36
		CCl_4	72		

[a] Special conditions used, ref 14.



(9)

29 **31**

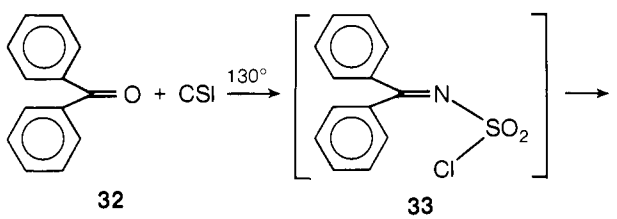
TABLE III. Oxazinones 39 from α,β-Unsaturated Ketones 37

R	R^2	R^3	% yield
CH_3	CH_3	CH_3	54
C_6H_5	CH_3	CH_3	39
C_6H_5	H	C_6H_5	57
CH_3	H	p-$CH_3OC_6H_4$	55
C_6H_5	H	p-ClC_6H_4	45
$C(CH_3)_3$	H	C_6H_5	54
$C_6H_5CH=CH$	H	C_6H_5	44

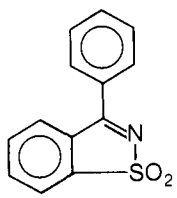
quantitative yield into 5,6-disubstituted uracils **31**, thus providing a new, facile, two-step synthesis of **31** from readily available ketone starting materials.[12,15]

2. Nonenolizable and Other Ketones

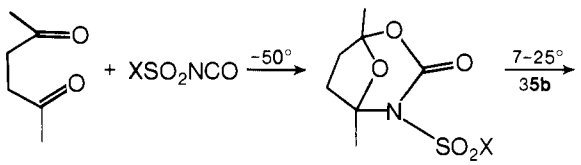
Benzophenone **32** reacts with CSI to form the benzoisothiazole dioxide **34** via intermediate azomethine **33**.[11] Azomethine formation was previously observed with diphenylcyclopropenone and tropone.[3] 2,5-Hexanedione produces the unusual cycloadducts **35a** and **35b** with CSI and FSI, respectively. Upon warming, **35b** loses CO_2 with azomethine formation.[11]



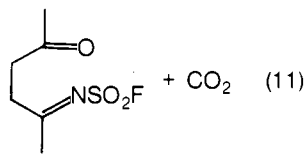
32 **33**



34 (28%) (10)



35a, X = Cl (41%)
b, X = F (88%)



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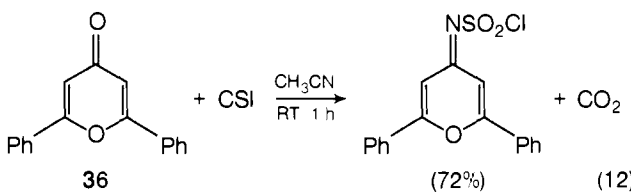
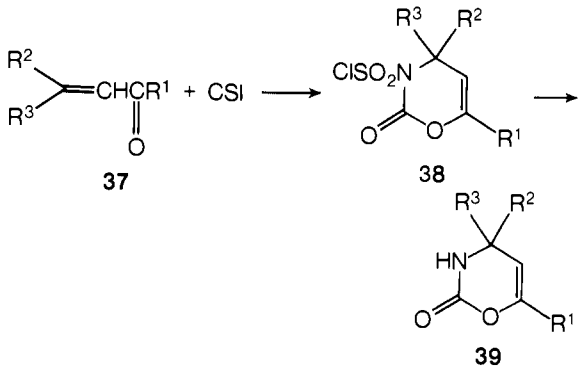
γ-Pyrones (e.g., **36**) have recently been reported to produce azomethines in 72–92% yields (eq 12).[17]

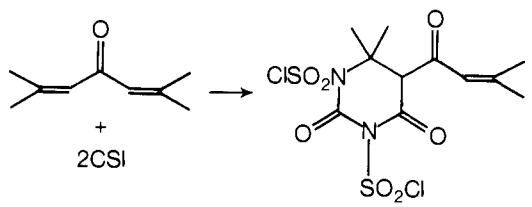


36 (72%) (12)

α,β-Unsaturated ketones **37** are converted into 3,4-dihydro-1,3-oxazin-2-ones **38** in 60–70% yield. Hydrolysis produces the unsubstituted compounds **39** (Table III).[11] This is formally a type I reaction. Phorone, on the other hand, reacts with 2 equiv of CSI to produce the dihydrouracil **40**.[11]



37 **38** **39** (13)

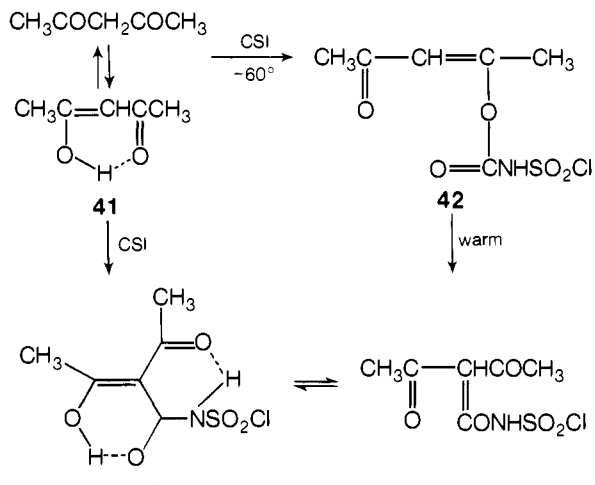


40 (84%) (14)

3. β-Diketones and β-Keto Acid Derivatives

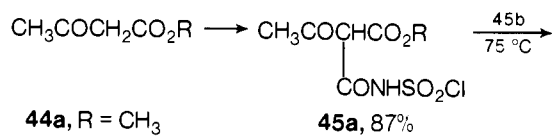
Acetylacetone **41** reacts rapidly with CSI at room temperature to produce the enolized β-ketoamide **43** in 67% yield (Scheme VIII). If the reaction is carried out at low temperature, however, enol carbamate **42** is produced in 87% yield. Compound **42** rearranges to **43** upon warming in solution via elimination and readdition of CSI.[11]

SCHEME VIII

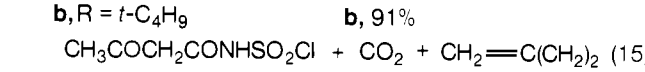


41 **42** **43**

Acetoacetic esters **44** react similarly to **41** and produce amides **45** (eq 15). In this case no intermediate enol carbamate could be isolated or observed at low temperature. Pyrolysis of **45b** produced β-ketoamide **46** along with CO_2 and isobutylene.[11]



44a, R = CH_3 **45a**, 87%
b, R = t-C_4H_9 **b**, 91%

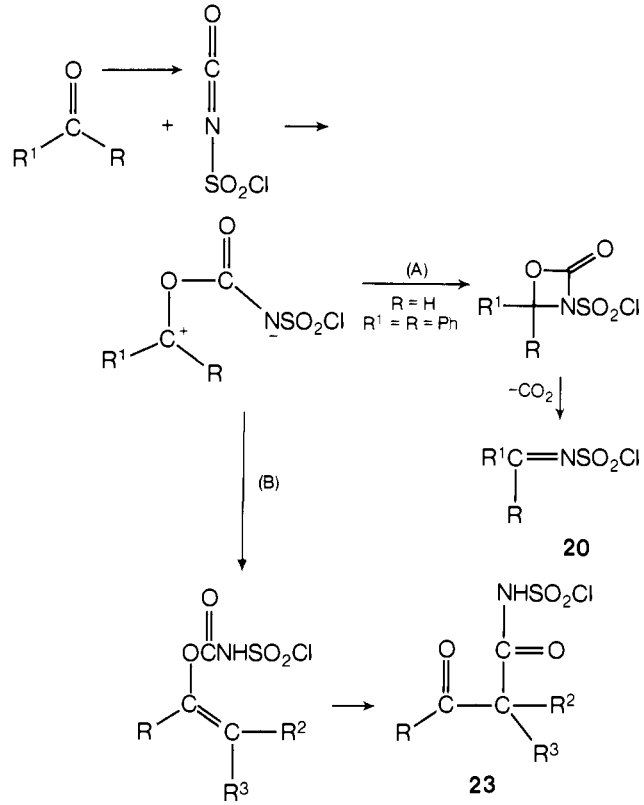


46, 75% (15)

TABLE IV. Triazinediones 49 from CSI and Schiff's Bases

R^1	R^2	% yield
C_6H_5	C_6H_5	100
p-$CH_3OC_6H_4$	C_6H_5	86
p-ClC_6H_4	C_6H_5	73
p-$NO_2C_6H_4$	C_6H_5	50
C_6H_5	p-$CH_3OC_6H_4$	50
C_6H_5	p-ClC_6H_4	60
C_6H_5	p-$NO_2C_6H_4$	0
C_6H_5	m-$NO_2C_6H_4$	78
C_6H_5	o-ClC_6H_4	50
C_6H_5	$C_6H_5CH_2$	60
C_6H_5	C_6H_{11}	65

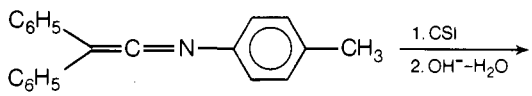
SCHEME IX



FSI is reported to undergo analogous reactions to those described above, and it produced products which are more stable than those derived from CSI.[11] Enamides and some enol ethers also have similar reactions at the β carbon (see section III.C.2.c). The dissimilar results in the reaction of various carbonyl substrates (aldehydes, enolizable ketones, nonenolizable ketones) with CSI may very well be due in all cases to initial attack by the carbonyl oxygen on the electron-deficient carbon of CSI. In the case of the more reactive and less hindered aldehydes, as well as in the case of nonenolizable ketones, four-membered ring formation may occur (path A) and leads to an azomethine **20.** In the case of enolizable ketones path B is followed and the enol carbamate undergoes rapid acyl migration from O to C (or elimination and addition of CSI) to produce β-keto amides **23** (Scheme IX).

4. Imines

The reaction of CSI with imines has been studied only to a limited extent. In addition to an earlier report[3] of a type I reaction with p-nitrobenzaldehyde N,N-tetramethylenehydrazone, only two new reports have appeared. Diphenyl-N-p-tolylketenimine **47** produces a 2:1 adduct with CSI believed to be diazine **48** in 84% overall yield.[18]



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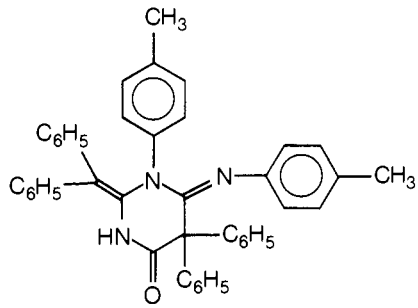
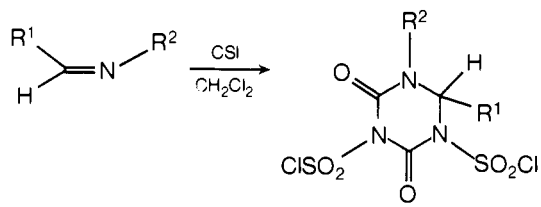
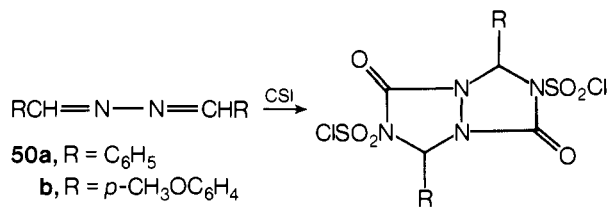


48 (16)

In a more extensive study, CSI has been found to yield 2:1 adducts with Schiff's bases.[19] The s-triazinediones **49** were formed in high yield (Table IV). As was predicted, azines **50** reacted with CSI to give the triazoles **51.**[19]



49 (17)

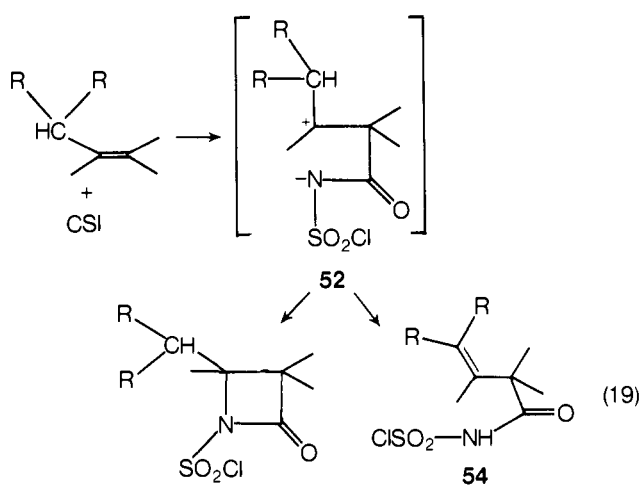


51 (18)

C. Olefins

1. Mechanism of the Cycloaddition

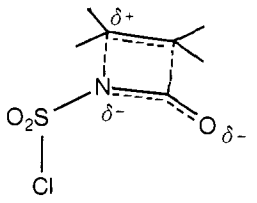
The most extensively studied examples of reaction type II are those involving addition to alkenes and polyenes.[1-3,20] Graf[21] originally proposed a two-step mechanism for this reaction, according to which the initial adduct is the 1,4-dipolar species **52**, which can then ring close to give β-lactam **53**, or form the unsaturated amide **54** via a proton shift. A good deal of work, including (1) the marked increase in reaction rate



52 (19)

53 **54**

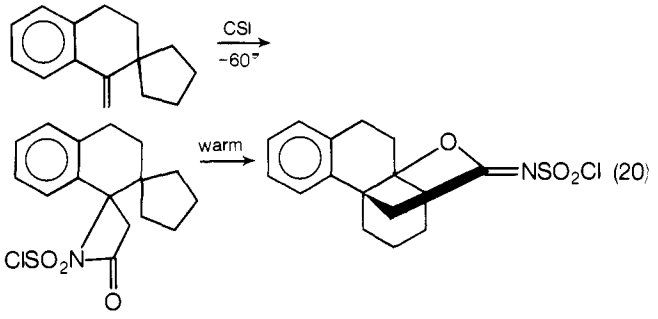
produced using polar as compared to nonpolar solvents, (2) the influence of olefin nucleophilicity on the rate of reaction, and (3) the simultaneous formation of **53** and **54** in numerous reactions, as well as the fact that the relative amounts of **53** and **54** produced in most cases were not influenced by changing reaction conditions, seemed to support this proposal.[20] Moriconi, on the other hand, has proposed a (near) concerted, thermally allowed $[_{\pi}2_s + {}_{\pi}2_a]$[22] cycloaddition, probably initiated by π-complex formation, and proceeding through the polar transition state **55.**[3,23] Among the evidence cited in



55

favor of this rationale are (**1**) the lack of rearrangement in the reaction of CSI with rearrangement-prone bridged bi- and tricyclic olefins,[3] (2) the stereospecific addition of CSI to cis and trans olefins,[3,20] and (3) the initial formation of (2 + 2) cycloadducts with conjugated dienes, which readily rearrange to more stable (4 + 2) adducts.[3,20,23]

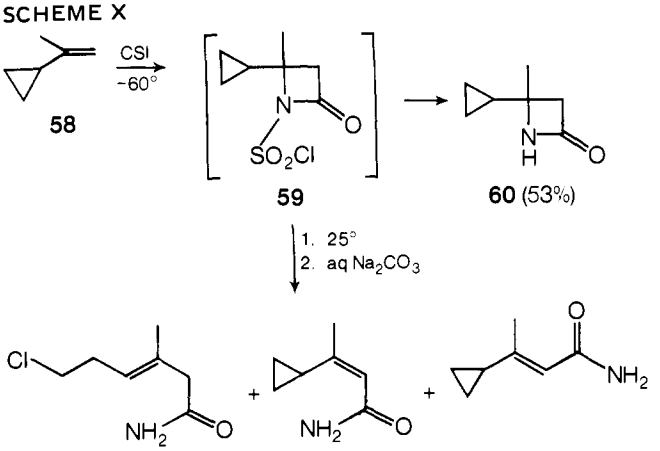
Other examples of the rearrangement of initially formed β-lactams have been reported. Doyle and Conway[24] reported that lactam **56** when warmed to room temperature produces **57.** Reaction of 2-cyclopropylpropene (**58**) with CSI at low



56 **57** (100%)

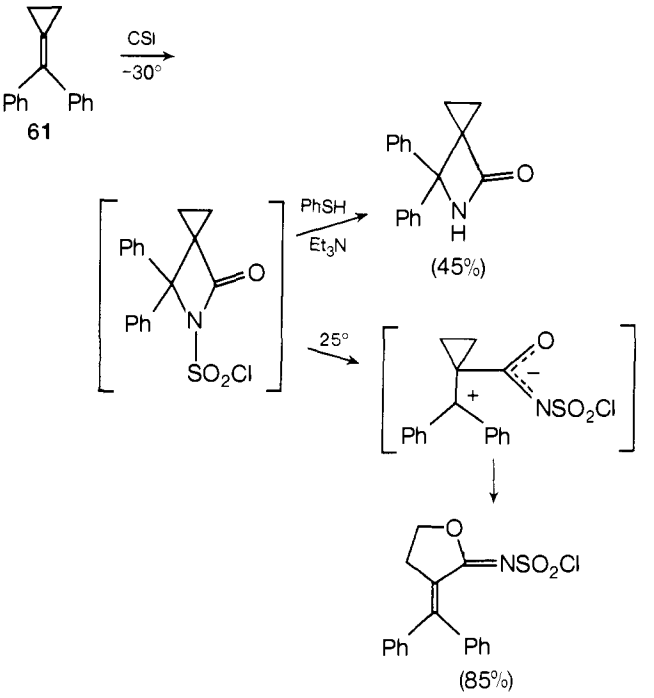
temperature allows isolation of β-lactam **60,** while reaction at room temperature yields only rearrangement products, thus indicating that **59** may be the primary intermediate (Scheme X).[25a] In a reinvestigation of a report by Dunkelblum,[26] Barton and Rogido[25b] have shown a similar mechanism to be operating with diphenylmethylenecyclopropane **61** (Scheme XI). The cycloadditions of CSI to olefins are always regiospecific with the C=O bonding to the olefin to produce the more stable incipient carbenium ion.

SCHEME X



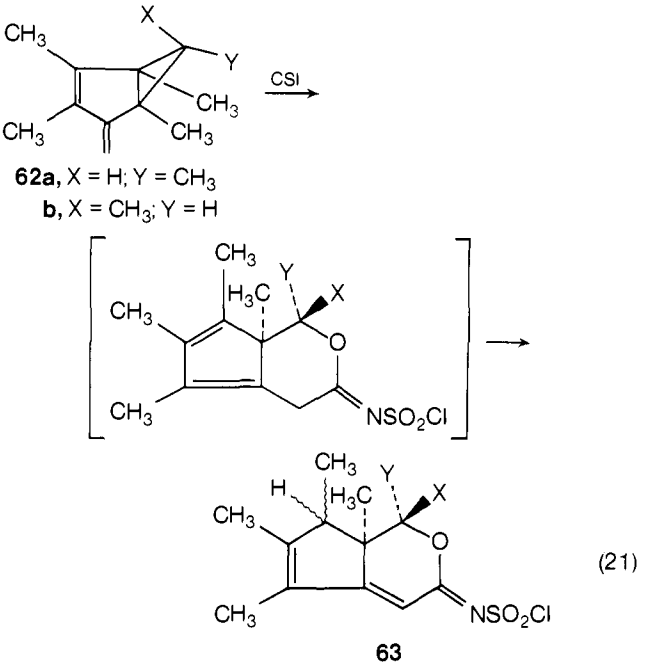
58 **59** **60** (53%)

SCHEME XI



61 (45%) (85%)

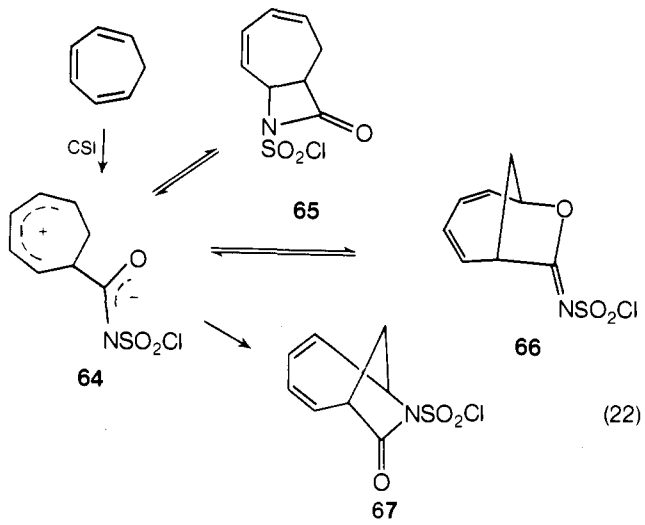
Reaction of CSI with the homofulvenes **62** occurs as a homo [6,2] cycloaddition with inversion at C-6 (eq 21). It has been stated that this result is in accord with a symmetry-allowed concerted reaction of the kind $[(_{\sigma}2_a + {}_{\pi}4_s) + {}_{\pi}2_s]$,[27] but a stepwise mechanism cannot be ruled out.



62a, X = H; Y = CH_3
b, X = CH_3; Y = H

63 (21)

The addition of chlorosulfonyl isocyanate to cycloheptatriene[28,29] was originally rationalized as a near-synchronous process leading to **1**,2- and or **1**,6-cycloaddition products, **65** and **67** followed by thermal and irreversible ring opening to the dipolar intermediate **64,** which then cyclized to **66** (eq 22).[28] In a reinvestigation of this reaction, Malpass[30a] has observed spectroscopically the slow formation of **66** accompanied by a small, stationary concentration of β-lactam **65.** Even more slowly, **66** is transformed into the thermodynamic product **67.** Cyclooctatriene reacted similarly to give the homolog of **67.** In addition, CSI was found not to react with cyclooctatriene in nonpolar solvents, in accord with a dipolar mechanism.



(22)

Camphene **68a** and CSI at −60 °C lead quantitatively to **70a,** which can be isolated as **70b** by hydrolysis (Scheme XII). Warming a solution of **70a** leads to rapid conversion to **71a** and **73a.** Although α-fenchene **68b** analogously produces **71b** and **73b,** no β-lactam intermediate could be observed or isolated.[30b]

Additional interesting results were obtained from the reaction of CSI with cyclohexadienes.[30c] For example, **74** in CCl_4 at room temperature for **1** h yielded **76b** (41%) and **77** (37%) (Scheme XIII). Longer reaction times allowed transformation into the more stable compounds **78** and **80.** More importantly, dissolution of isolated **77** in CH_2Cl_2 was shown by spectroscopy to produce a small amount of **76a,** whose concentration remained constant until complete conversion to **78** and **80a** was achieved. Since dipole **75** must be an intermediate, this is the first unambiguous demonstration that a β-lactam is accessible from a 1,4-dipole.

The foregoing results have led Malpass[30] to propose that 1,4-dipoles still merit consideration as primary intermediates in CSI–olefin cycloadditions, giving 1,2-addition under kinetic control and rearrangement products under thermodynamic control. Moreover, the results of a recent kinetic study on substituted styrenes have been found to be totally inconsistent with concerted cycloaddition.[31] Perhaps the real answer is that the substitution on the olefin in question (stabilization of charges) determines the extent of C–N bond formation in relation to C–C bond formation in the transition state (or intermediate as the case may be). Some examples may be concerted or near-concerted, while others proceed stepwise via a true dipolar intermediate, with many more examples lying somewhere between the two extremes.

SCHEME XII

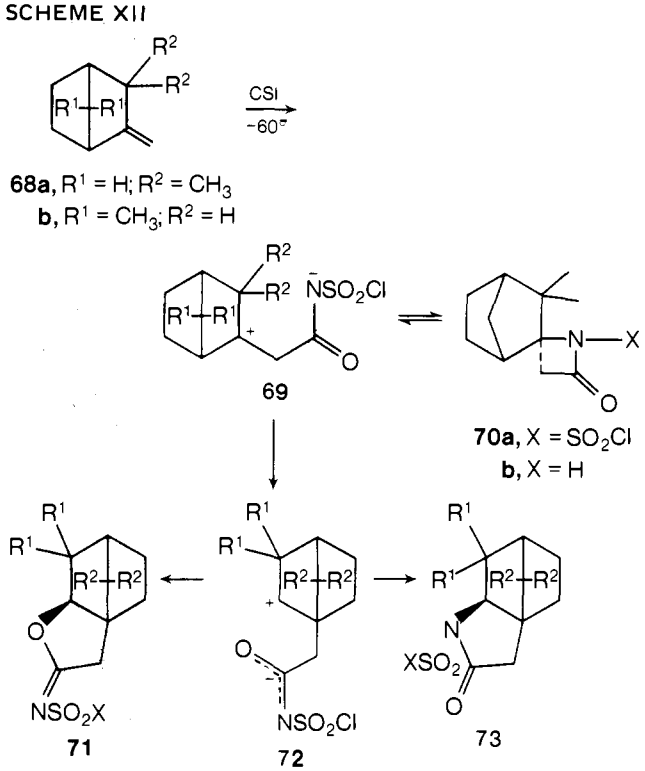
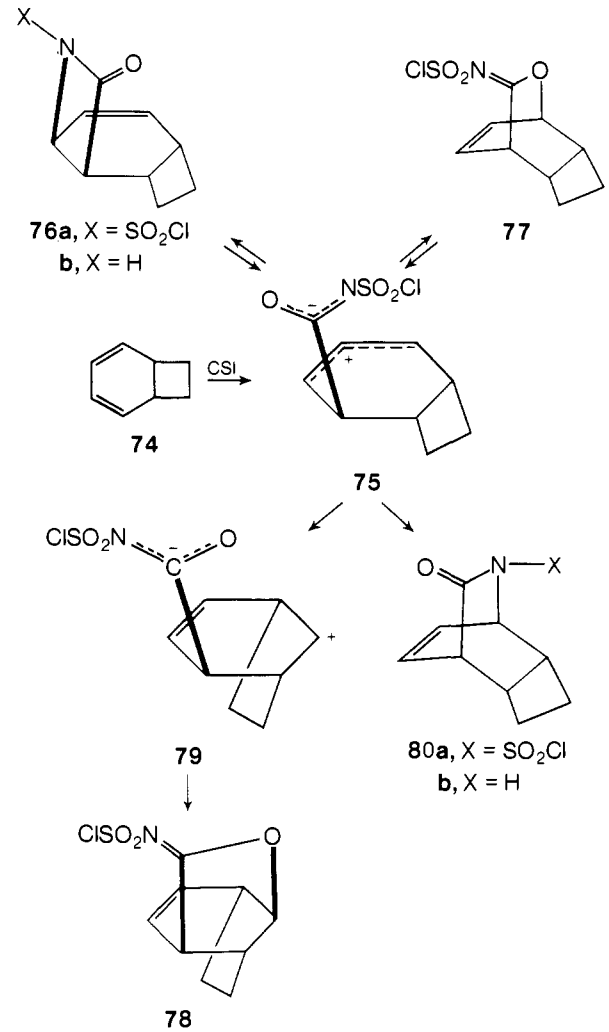


TABLE V. Products from Monoterpene Olefins and CSI

Olefin	Product (% yield)		Ref
α-Pinene	82 (not stated)	83 (50) 84 (20)	32
	82 (65)	83 (40)	33
	82 (75)	83 (60)	34
β-Pinene	86b (70)	85 (70)	32
	86b (31.3)	89 (12.6) 90 (6.5)	33
Δ^3-Carene	92 (72)		33

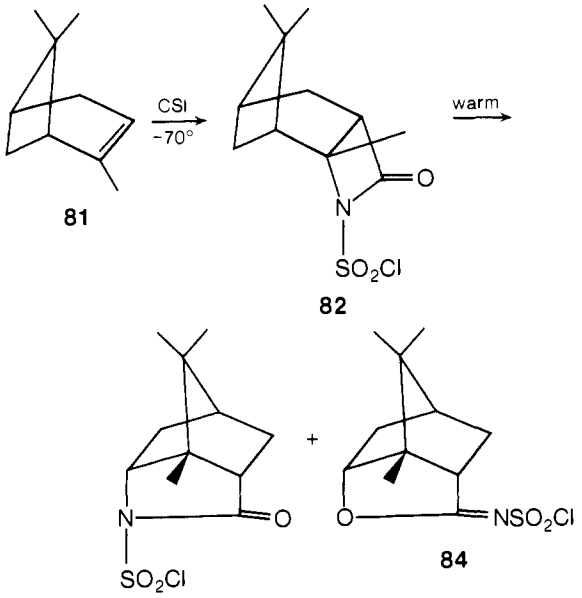
SCHEME XIII



2. Other Monoterpene Olefins

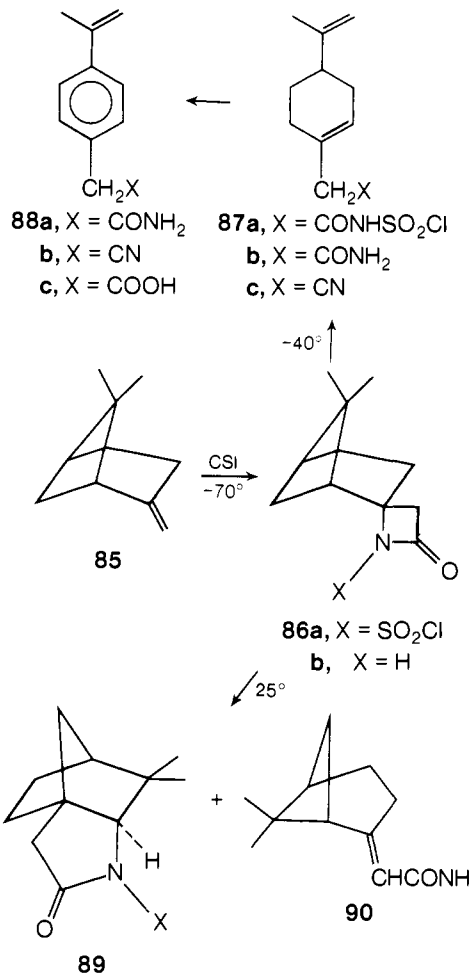
In addition to the study on the reaction of CSI with camphene **68a** and α-fenchene **68b,**[30b] other bicyclic monoterpene olefins have also been studied.[32-34] α-Pinene **81** at −70 °C produces β-lactam **82,** which rearranges on warming to **83** and **84** (eq 23) (Table V).

Reaction with β-pinene **85** produces the very unstable *N*-chlorosulfonyl-β-lactam **86a** (Scheme XIV), which can be isolated as **86b** (Table V). According to Malpass,[32] warming a

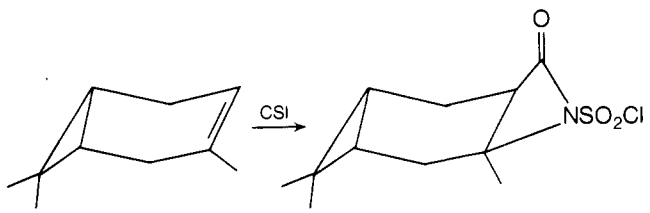


(23)

SCHEME XIV



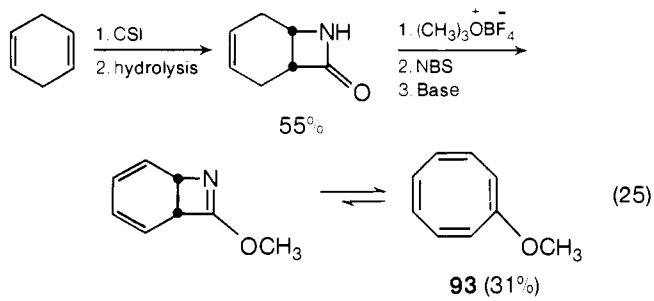
solution of **86a** to −40° causes rapid rearrangement to **87a.** Support for structure **87a** is provided[32] by conversion to **87b, 87c,** and **88b,** as well as to the previously known **88a** and **88c.** On the other hand, Sasaki et al.[33] report that the thermal rearrangement of **86a** at room temperature affords a complex product mixture from which **89** and **90** can be obtained (Table V). Lactam **89** was identified by comparison of its spectral properties with those of the similar compound **73a** from camphene. Reaction of CSI with Δ^3-carene **91** produces the stable β-lactam **92** (Table V). The seemingly inconsistent results obtained with monoterpene olefins appear to be due to slight variations in reaction conditions and mode of workup. This again points out the striking sensitivity of CSI reactions to changing conditions.



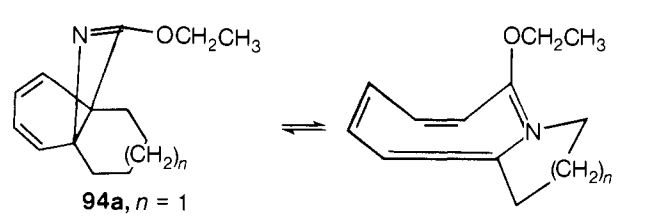
(24)

3. Monoenes, Dienes and Vinylcyclopropanes

The cycloaddition of CSI with **1,4**-dihydrobenzene derivatives has been used as the first step in the synthesis of 2-alkoxyazocines.[35] For example, **93** was obtained by the sequence shown in eq 25. Similarly, the annelated compounds **94** were prepared and their tautomeric equilibria studied. With **94a** and **94b,** the equilibrium lies entirely in favor of the azabicyclooctatriene tautomer, whereas **94c** can be displaced in favor of the bridged azocine at temperatures above 100 °C. However, **94d** exists as the azocine at room temperature.

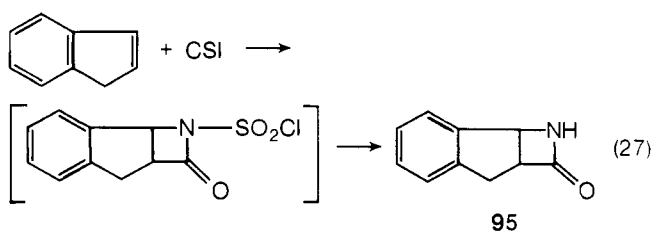


(25)



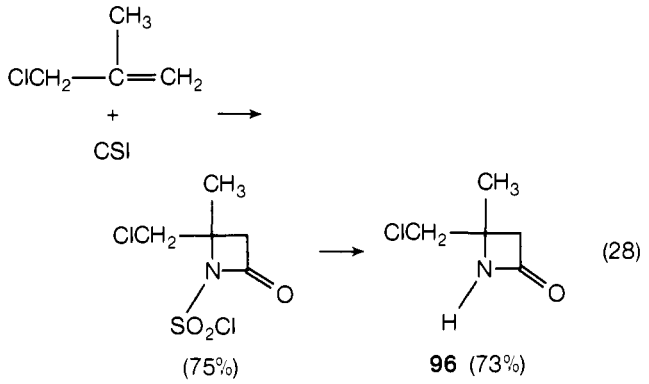
(26)

Two independent reinvestigations of the reaction of CSI with indene, originally reported to yield only indene-2-*N*-chlorosulfonylcarboxamide,[21] have shown that if the reaction is carried out at low temperature, β-lactam **95** may be isolated. Using essentially identical procedures, yields of 20–25%[36] and 98%[37] were reported.



(27)

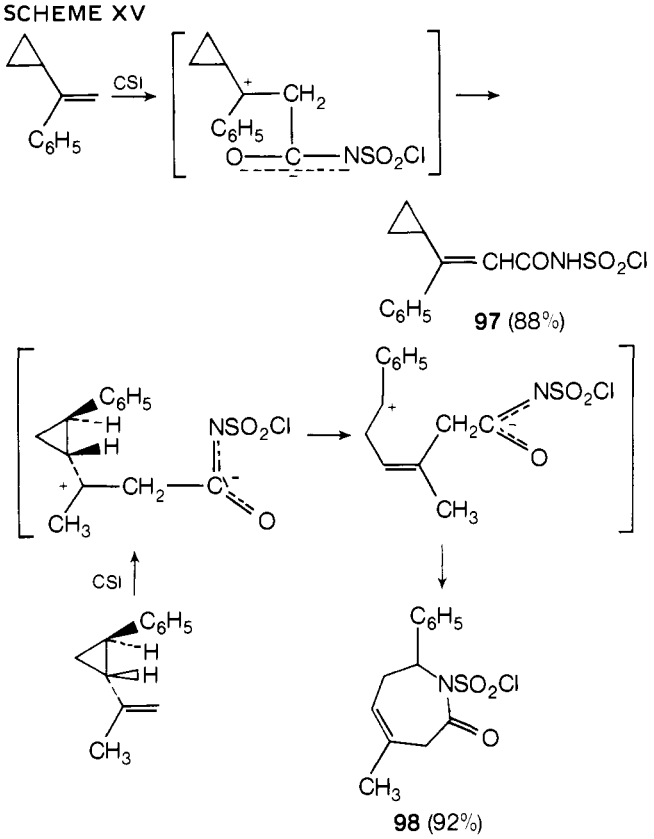
The interesting β-lactam **96** is obtained from methallyl chloride and CSI (eq 28).[38] Nucleophilic substitutions of the chloride in **96** proceed sometimes with maintenance of the β-lactam structure and sometimes with ring expansion to a five-membered ring.



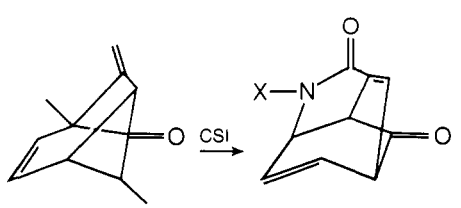
(28)

Treatment of α-cyclopropylstyrene with CSI produces unsaturated amide **97** (type I reaction), whereas *trans*-2-phenylisopropenylcyclopropane yields only **98** (Scheme XV).[39a] The results are rationalized on the basis of the different stabilization available to the dipolar intermediates.

SCHEME XV



A similar explanation can be used to rationalize 6-ring formation in the reaction of CSI with a divinylcyclopropane (eq 29).[39b]

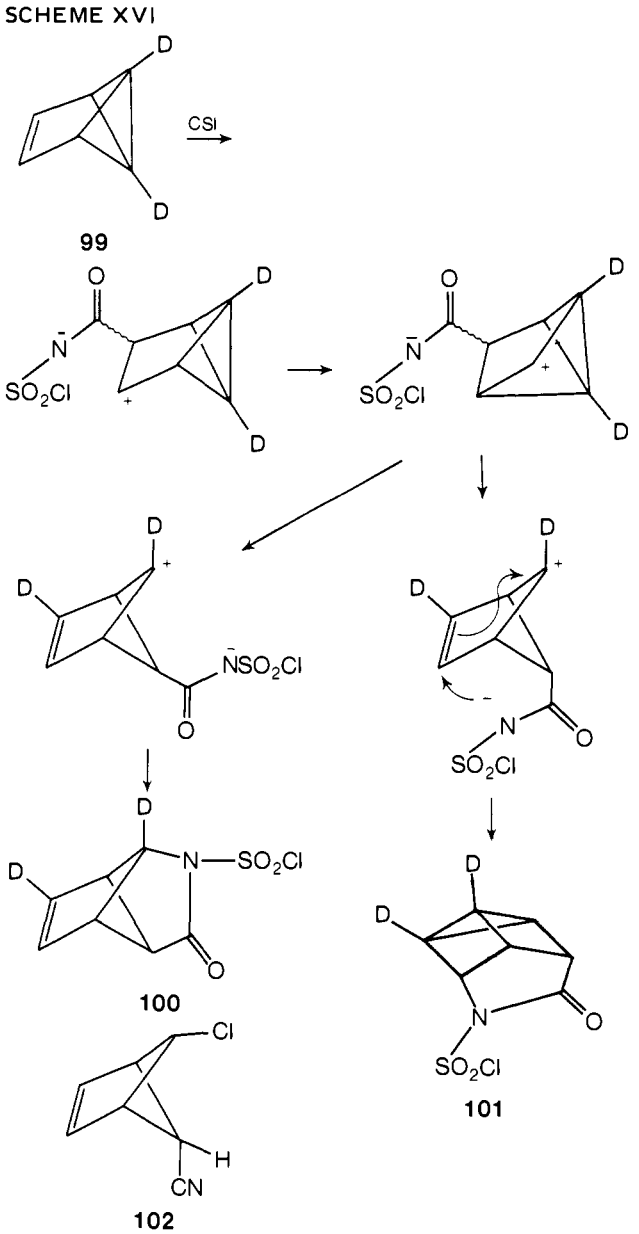


70–75% (29)

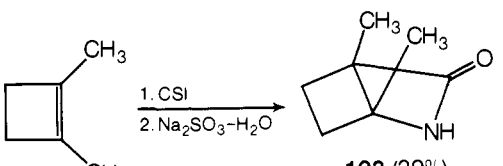
A somewhat more exotic vinylcyclopropane, benzvalene **99**, reacts with CSI, giving likewise rearranged products **100** and **101** (Scheme XVI).[40] The latter and another unidentified adduct were formed in a ratio of 2:6:2. Treatment of the crude reaction mixture with DMF gave chloronitrile **102** (31%) and an isomer (10%) of **102.**

1,2-Dimethylcyclobutene and methylenecyclobutane react

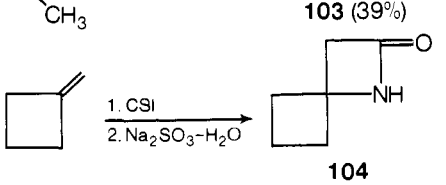
SCHEME XVI



in a straightforward manner with CSI to give the corresponding lactams **103** and **104.**[41]



(30)



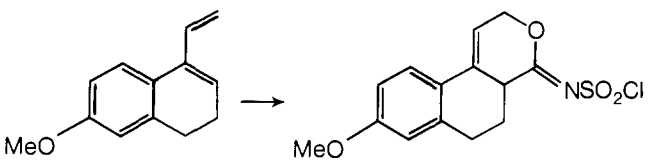
(31)

Addition of CSI to the vinyldihydronaphthalene **105** at −70 °C produces iminolactone **106** in 50% yield.[42] Warming a solution of **106** above 0° leads to slow conversion into lactam **107.** Thus, CSI is shown to be useful for the synthesis of complex nitrogen heterocycles. Various transformation of **106** and **107** are described.[42]

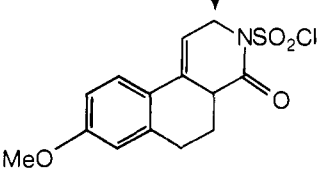
CSI has proven useful in the modification of unsaturated polymers. For example, isoprene and butadiene homo- and copolymers are treated with CSI, then hydrolyzed to give the

TABLE VI. Product Distributions from 117 and CSI

Compd	R^1	R^2	R^3	% yield (total)	Ratio 120:121
a	H	H	H	67.0	
b	H	CH_3	H	73.0	68.5:31.5
c	H	OCH_3	H	56.5	45.5:54.5
d	H	$OCOCH_3$	H	57.5	76.0:24.0
e	CH_3	OCH_3	H	52.5	31.5:68.5

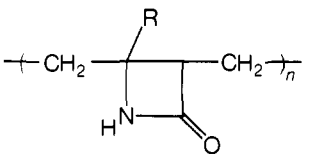


105 106



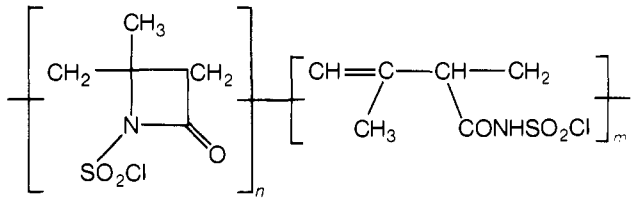
107 (32)

modified polymers **108** which have improved chemical resistance, oxidation resistance, and heat stability as compared to the unmodified polymers.[43] Also, *cis*-1,4-polyisoprene has



108

been treated with CSI in benzene to produce **109**, basic hydrolysis of which gives polymer **110** that exhibits polyelectrolyte behavior (eq 33).[44] Heating **110** with acid causes N–S splitting and produces a polyampholyte.[44]



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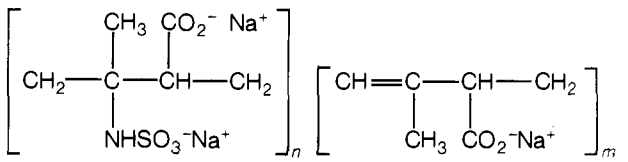
(33)

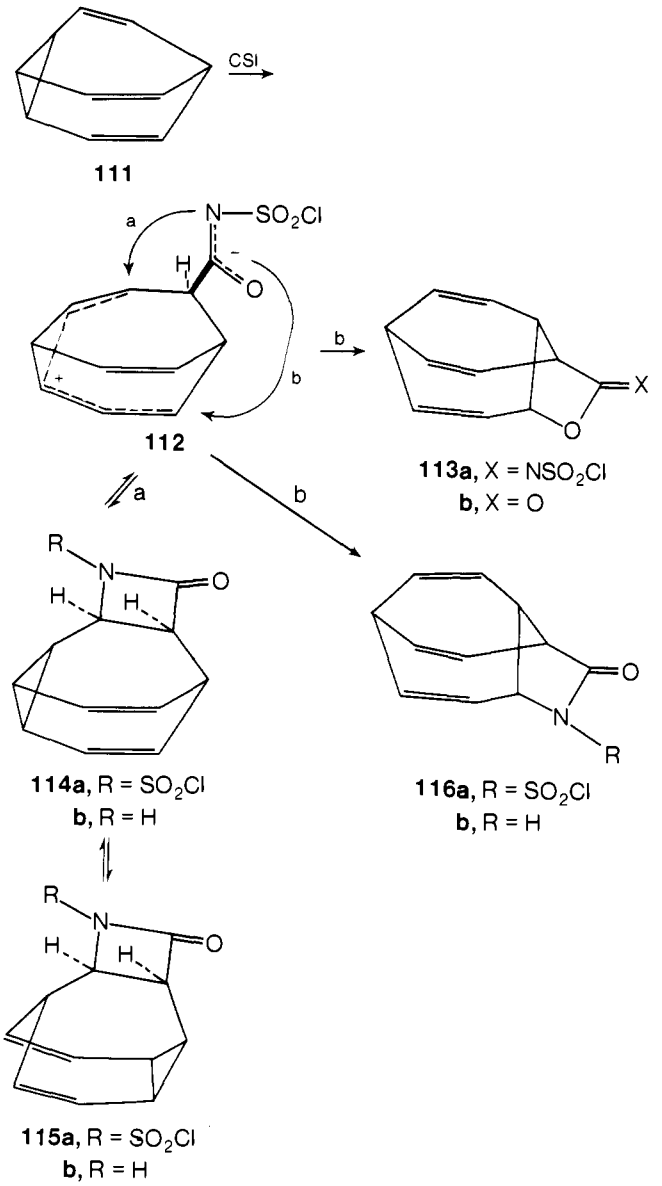


110

4. *Bicyclic Polyenes*

In addition to the numerous synthetic studies utilizing CSI, this uniparticulate electrophile (an electrophile incapable of fragmentation)[45] has also been employed as a tool to study electrophilic additions to a number of systems. Such a reagent is unusually effective in generating and trapping carbonium ions in polyenic systems where cationic rearrangement or competitive cyclization is possible. This type of study on

SCHEME XVII



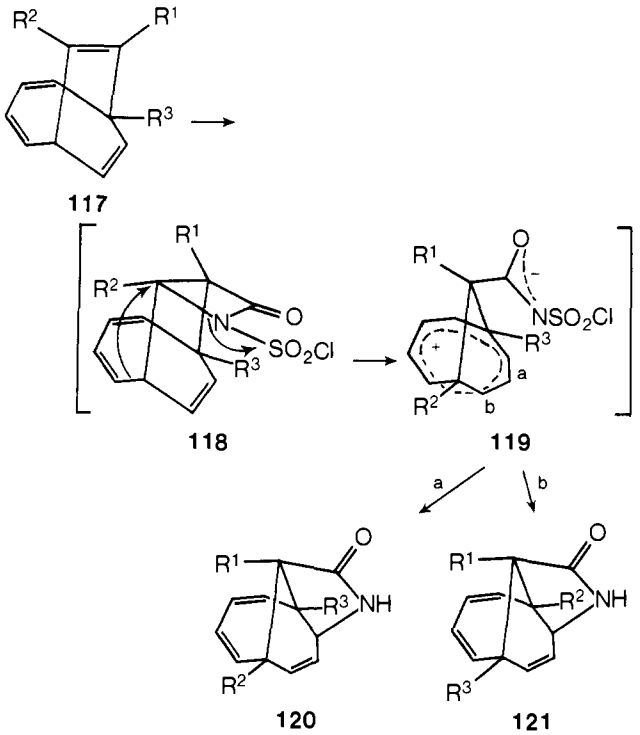
111 112 113a, X = NSO_2Cl b, X = O 114a, R = SO_2Cl b, R = H 115a, R = SO_2Cl b, R = H 116a, R = SO_2Cl b, R = H

cyclooctatetraene has previously been described.[20] More recently, cyclooctatetraeneiron tricarbonyl has been shown[46] to react in the same manner as the uncomplexed polyolefin.

In a dual synthetic and mechanistic study, Paquette[47] has found that the addition of CSI to bullvalene **111** leads to competitive 1,2 and 1,6 cycloaddition. Reaction at room temperature, followed by hydrolysis, affords lactone **113b** (31%), β-lactam **114b** ⇌ **115b** (19%), and lactam **116b** (15%), while reaction at 40° yields **113b** (15%), **114b** ⇌ **115b** (2%), and **116b** (17%). Apparently, **114a** ⇌ **115a** is the kinetic product of cyclization from zwitterion **112**, but is unstable thermodynamically relative to **113a** and **116a** (see Scheme XVII).

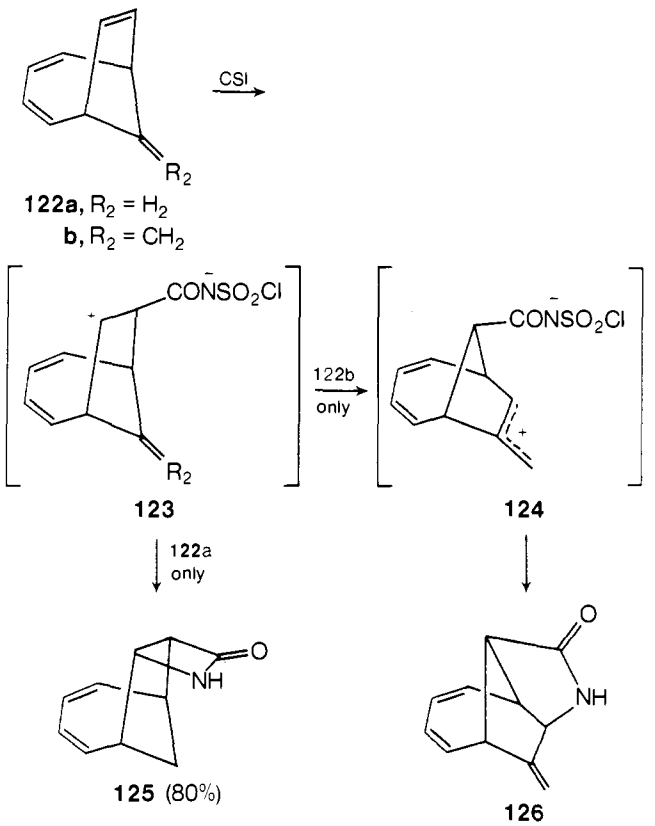
The addition of CSI to bicyclo[4.2.2]deca-2,4,7,9-tetraene derivatives **117** produces rearranged tricyclic lactams **120** and **121** derived from 1,4-bishomotropylium zwitterionic intermediates **119** (see Scheme XVIII, Table VI).[48] The initial formation of β-lactams **118** (either stepwise or concerted) was verified, and the formation of **119** is believed to provide the driving force for rearrangement. Additional evidence supporting the importance of charge delocalization in the skeletal rearrangement is provided by the reactions of CSI with **122a** and **122b**. Rearrangement of cation **123a** would provide no additional stabilization; therefore, β-lactam **125** is isolated as the sole product. Rearrangement of **123b**, on the other

SCHEME XVIII



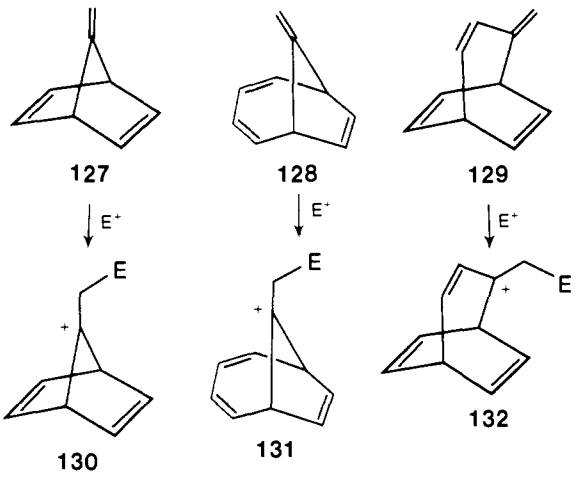
hand, leads to an allyl carbonium ion **124** and the rearranged lactam **126** is produced as the major product (Scheme XIX).

SCHEME XIX

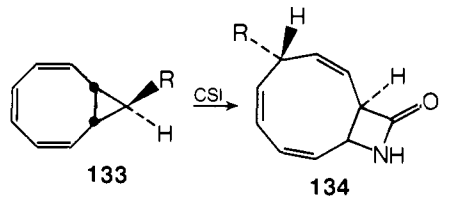


Paquette has also studied the use of CSI as a probe of possible bicycloaromatic and antibicycloaromatic carbonium ion character.[49] Since electrophilic attack at the exocyclic methylene center in compounds **127**, **128**, and **129** would lead to a bicycloaromatic cation (**130**) and two antibicycloaromatic cations (**131** and **132**), these and similar compounds including benzologs were allowed to react with CSI (Scheme XX). The results obtained are interpreted to be a reflection of the exceptional stability of the 7-norbornadienyl cation **130** and to be convincing evidence that cation **131** is not particularly stabilized. Unequivocal evidence concerning cation **132** could not be obtained.

SCHEME XX



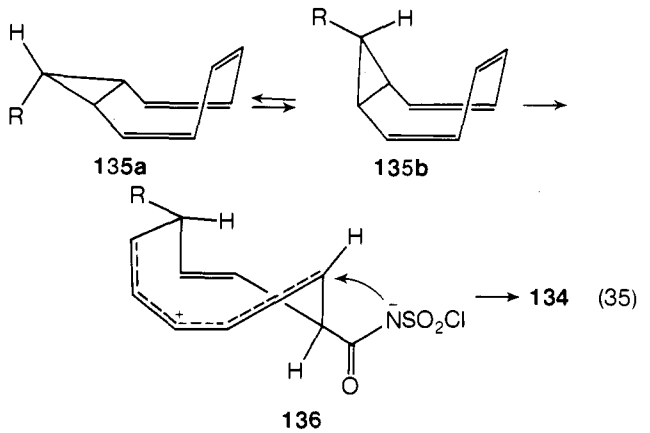
Reaction of CSI with *cis*-bicyclo[6.1.0]nonatrienes **133** occurs with an unusually high degree of stereoselectivity, producing *trans*-10-azabicyclo[7.2.0]undeca-2,5,7-trienes **134**.[50] Similar results are obtained with methyl-substituted



(34)

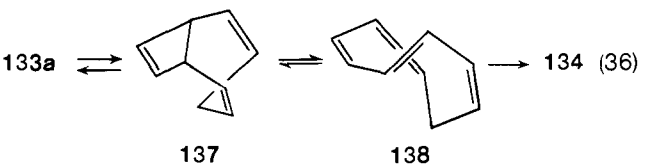
a, R = H (60%); **b**, R = CH_3 (56%); **c**, R = Cl (15%)

derivatives of **133a**. This impressive stereocontrol has led the authors[50] to propose that the reaction takes place by initial exo bonding of the electrophile to C_3 of the folded conformation **135b**, leading to the *trans*-1,3-bishomotropylium ion **136**. Collapse of the zwitterion produces the product with



(35)

proper stereochemistry. More recently, a kinetic study of the reaction with **133a** has produced parameters which are more consistent with initial valence isomerization to **137** and electrocyclic ring-opening to **138**, followed by normal (2 + 2) cycloaddition with CSI.[51] The kinetics of the analogous reaction

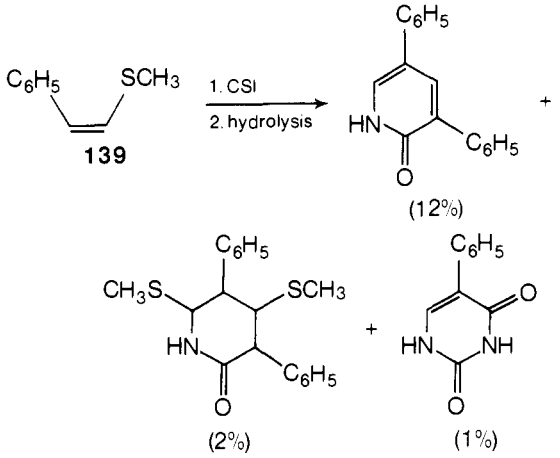


(36)

with tetracyanoethylene have been interpreted similarly.[52] This mechanism, however, requires a highly specific conrotatory opening of **137** in only one of two possible modes in order to explain the results obtained with the substituted derivatives. More work will be necessary to verify the mechanism of this reaction.

5. Heterosubstituted Olefins

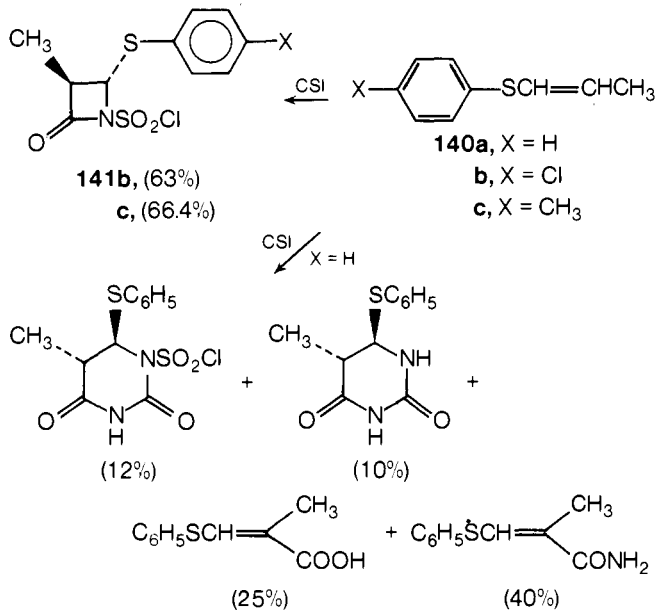
The penicillin and cephalosporin antibiotics all contain sulfur-substituted 2-azetidinone (β-lactam) rings. This fact has encouraged the study of the reaction of CSI with sulfur-substituted olefins.[53] *cis*-β-Methylthiostyrene **139**, when allowed



(37)

to react with CSI, produces a mixture of three products in low yield (eq 37). Reaction with **1**-phenylthio-**1**-propene **140** also failed to produce the desired β-lactam system giving instead a mixture of four products in high yield (Scheme XXI). On the other hand, substituted β-lactams **141b** and **141c** are obtained from **140b** and **140c** in good yield.[53a] The S,N-disubstituted olefin **142** undergoes no incorporation of CSI. A mechanism involving addition/elimination of CSI has been proposed to account for the formation of the observed products.[53b]

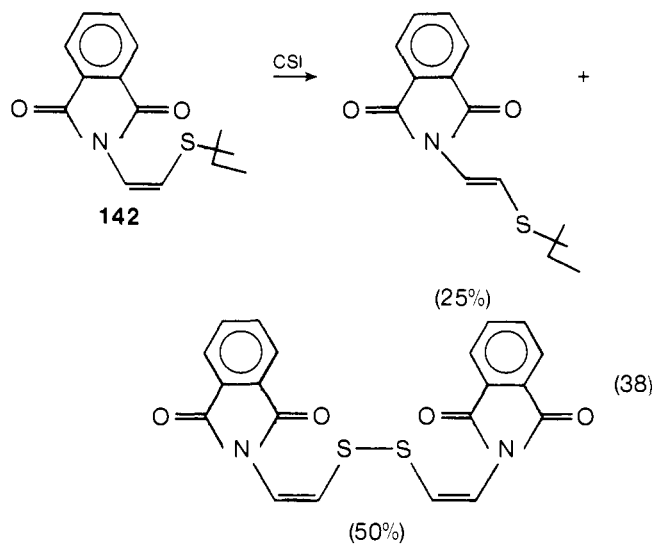
SCHEME XXI



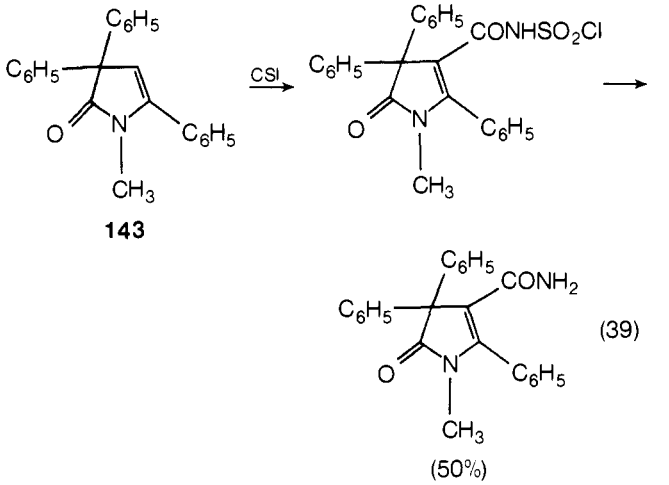
The cyclic enamides **143** and **144** have been shown to lead only to unsaturated amides upon reaction with CSI (eq 39, 40).[54] Similarly, the dihydroquinolines **145** and **147** are reported to give the nitriles **146** and **148** (eq 41, 42). No evidence as to the nature of the intermediates was given.[55]

TABLE VII. 4-(Acyloxy)azetidinones 153 from Vinyl Esters and CSI

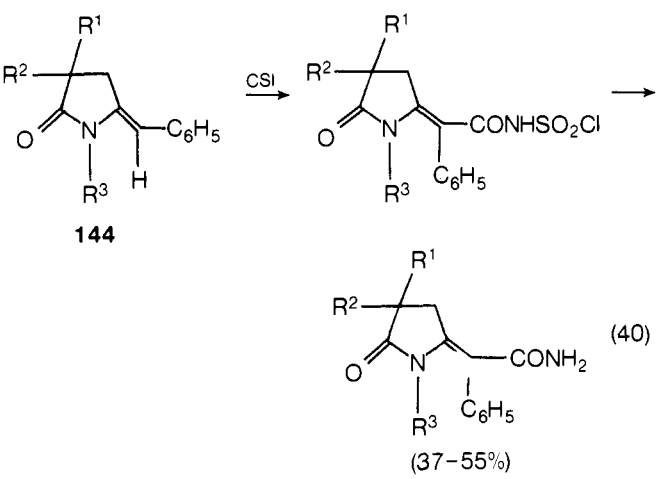
Ester	R^1	R^2	R^3	% yield
a	CH_3	H	H	40–43
b	C_2H_5	H	H	56
c	$(CH_3)_2CH$	H	H	48
d	$(CH_3)_3C$	H	H	65
e	C_6H_5	H	H	51
f	CH_3	CH_3	H	33
g	CH_3	CH_3	CH_3	55
h	$C_6H_5C(CH_3)H$	H	H	36



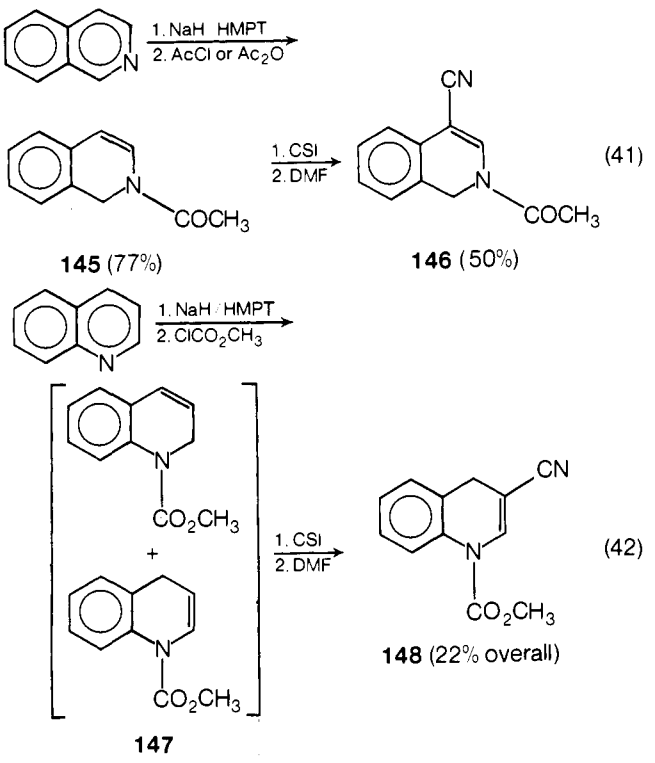
(38)



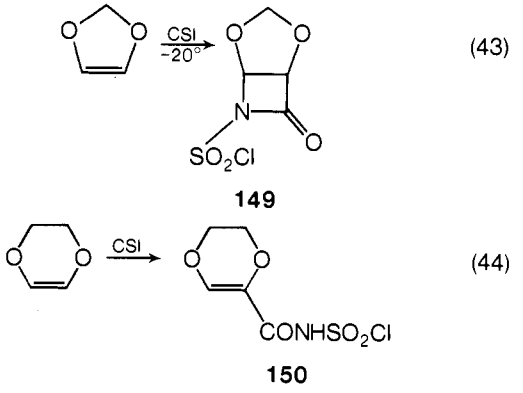
(39)



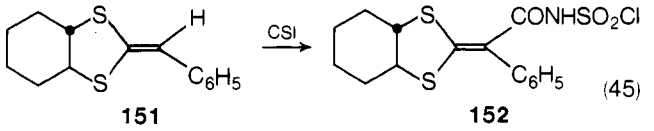
(40)



The β-lactam **149** obtained from CSI and 1,3-dioxole in quantitative yield is reported to decompose on attempted purification. Dihydro-*p*-dioxin, however, produces only the unstable amide **150.**[56]



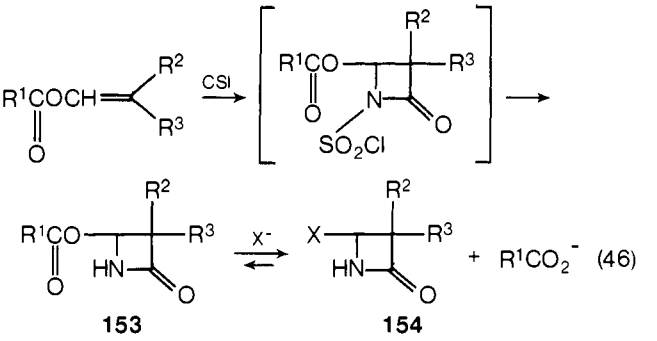
Ketene thioacetal **151** undergoes ready reaction with CSI; once again, however, only the open chain amide **152** is formed.[57]



The difficulties associated with the attempted synthesis of heterosubstituted β-lactams described above have recently been elegantly overcome by the use of vinyl esters as the olefinic components (eq 46).[58] The acid-, base-, and heat-sensitive azetidinones **153** (Table VII) have to be prepared under carefully controlled conditions. The synthetic importance of this reaction for penicillin related compounds comes from the fact that the acyloxy group can be readily exchanged with a variety of nucleophiles, producing 4-thio-, 4-(aryloxy)-, 4-(alkyloxy)-, 4-(arylsulfonyl)-, 4-(alkylsulfonyl)-, 4-azido-, and 4-phthalimido-β-lactams in good to excellent yields. In fact, in the series $RCOO^-$, RSO_2^-, N_3^-, $R\text{-}O^-$, RS^-, each nucleophile is capable of displacing any other nucleophile, lying to the left of it, from the 4 position of β-lactam **154.** This displacement occurs with racemization.[58]

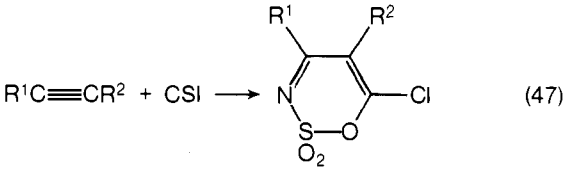
TABLE VIII. Oxathiazines 155 from Acetylenes and CSI

Ester	R^1	R^2	% yield
a	CH_3	CH_3	42
b	C_2H_5	C_2H_5	95
c	$n\text{-}C_3H_7$	$n\text{-}C_3H_7$	86
d	$n\text{-}C_3H_7$	CH_3	92
e	$(CH_3)_3C$	CH_3	51
f	C_6H_5	CH_3	86
g	C_6H_5	H	48
h	$n\text{-}C_3H_7$	$CH_2CH{=}CH_2$	90

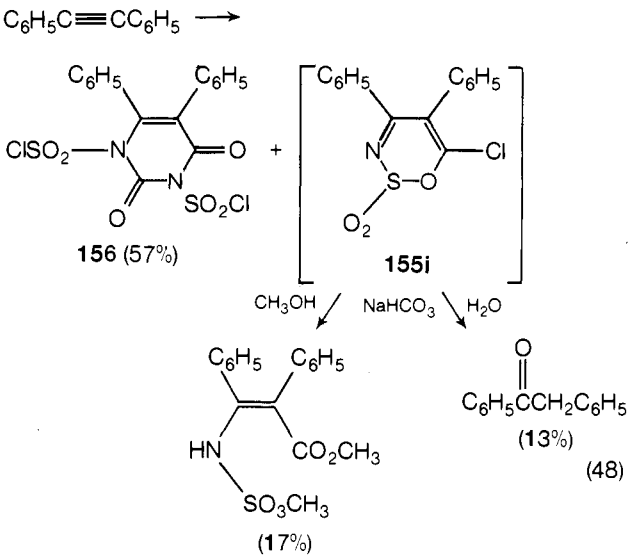


D. Acetylenes and Allenes

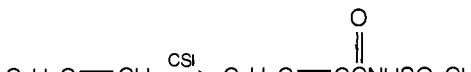
The initial results on the reaction of CSI (and FSI) with acetylenes have been reviewed.[3,20] Some additional x-ray structural analyses of the products have appeared.[59] Moriconi and Shimakawa[60] have extended this reaction (Table VIII) and have described numerous reactions of the product 1,2,3-oxathiazine 2,2-dioxides **155** with nucleophiles. Certain acetylenes, however, react differently.[60]



Diphenylacetylene produced 1,3-bis(chlorosulfonyl)-5,6-diphenyluracil (**156**) as the major product (eq 48). The minor product is believed to be **155i** on the basis of the reactions



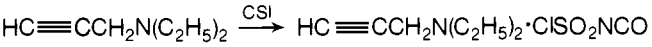
indicated. 1-Hexyne and CSI form the acetylenic product **157** in low yield. 3-Diethylamino-1-propyne and 1-diethylamino-



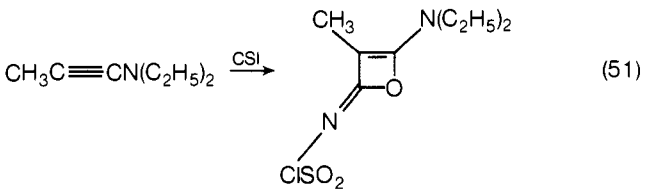
(49)

157

1-propyne react with CSI at low temperature to give products believed to be the tertiary amine–CSI salt **158** and the oxete **159.**[60]



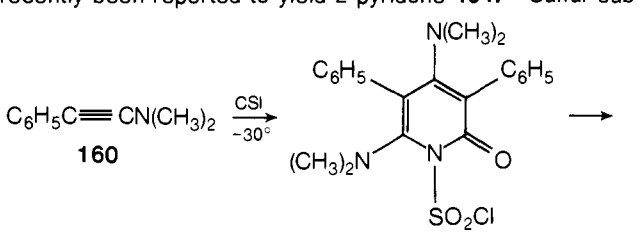
158 (95%) (50)



(51)

159 (100%)

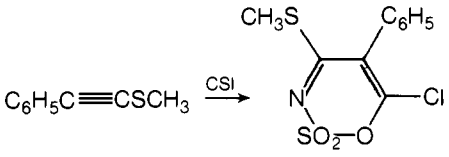
Another ynamine, dimethylphenylethynylamine (**160**), has recently been reported to yield 2-pyridone **161.**[61] Sulfur-sub-



(52)

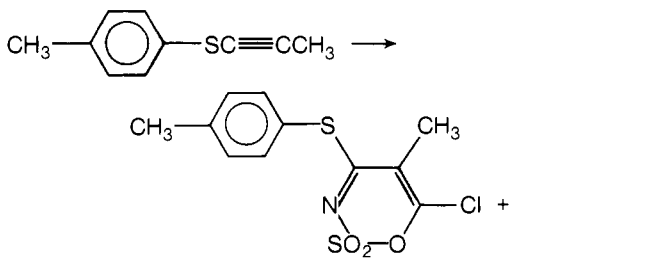
161 (55%)

stituted acetylenes, however, appear to react somewhat more normally.[61] Methyl phenylethynyl sulfide produces oxathiazine **155j** in 16.1% yield, whereas *p*-tolyl 1-propynyl

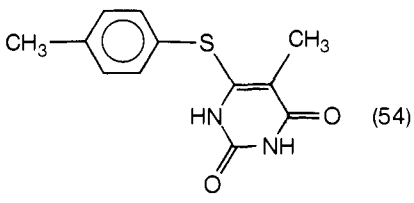


(53)

155j



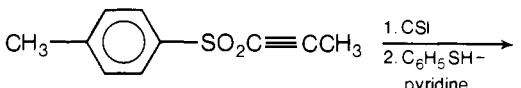
155k



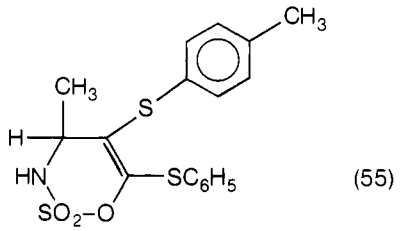
(54)

(5%)

sulfide gives **155k** in 34.9%. The dihydrooxathiazine **163** is obtained in only 1.4% yield from acetylenic sulfone **162.**



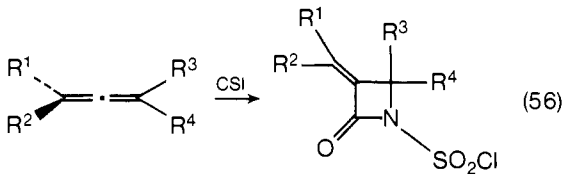
162



(55)

163

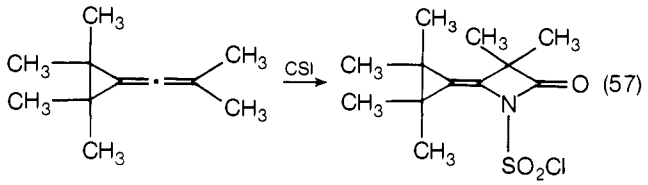
With simple allenes, CSI addition occurs principally at the central carbon atom to produce 3-alkylidene-2-azetidinones **164.**[3,20] Alkenylidenecyclopropanes, on the other hand, ex-



(56)

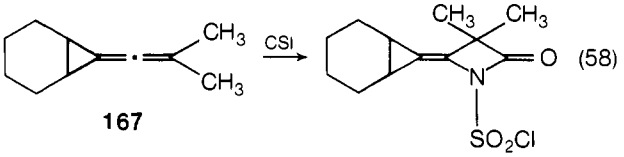
164

hibit a more complicated behavior toward CSI. 2-Methyl-1-(tetramethylcyclopropylidene)propene **165** reacts with CSI to form lactam **166** exclusively—the result of electrophilic attack at the terminal allenic carbon.[62] Allene **167** reacts similarly.[63]



(57)

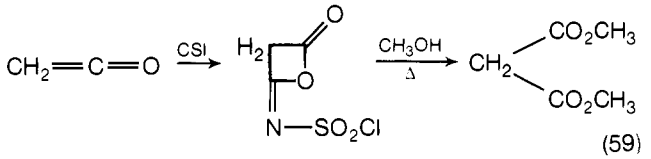
165 **166** (50%)



(58)

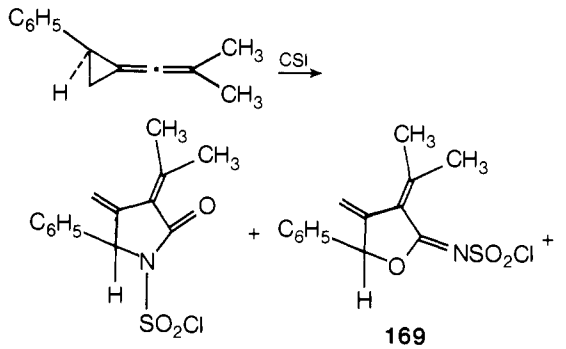
167

By contrast, ketene reacts with CSI to produce dimethyl malonate after heating with methanol (eq 59).[2] Other alkenyl-

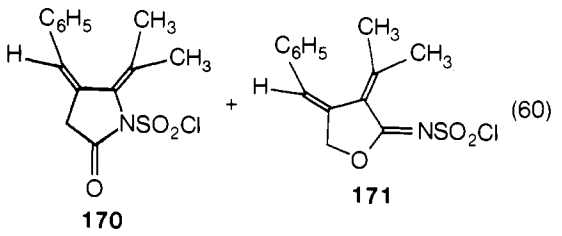


(59)

idenecyclopropanes give a variety of products.[63,64] 2-Phenylisobutenylidenecyclopropane is reported to yield **168** and **169** as the main products in approximately equal amounts.[63] An independent study, however, reports **168** (26.4%), **169** (19%), **170** (30.5%), and **171** (17%).[64] These products are the result of initial attack by CSI at the central allenic carbon followed by cyclopropane ring opening. The ring-opened products **169–171** were obtained optically active when the starting allene was chiral. A detailed study of the stereochemical aspects of this reaction has led the authors[64b] to explain the results in terms of the relative rates of bond rotation vs. collapse of the dipolar intermediate formed in the reaction. Other alkenylidenecyclopropanes react with CSI to produce both cyclopropane ring-retained and ring-opened products.[64a]



168 169



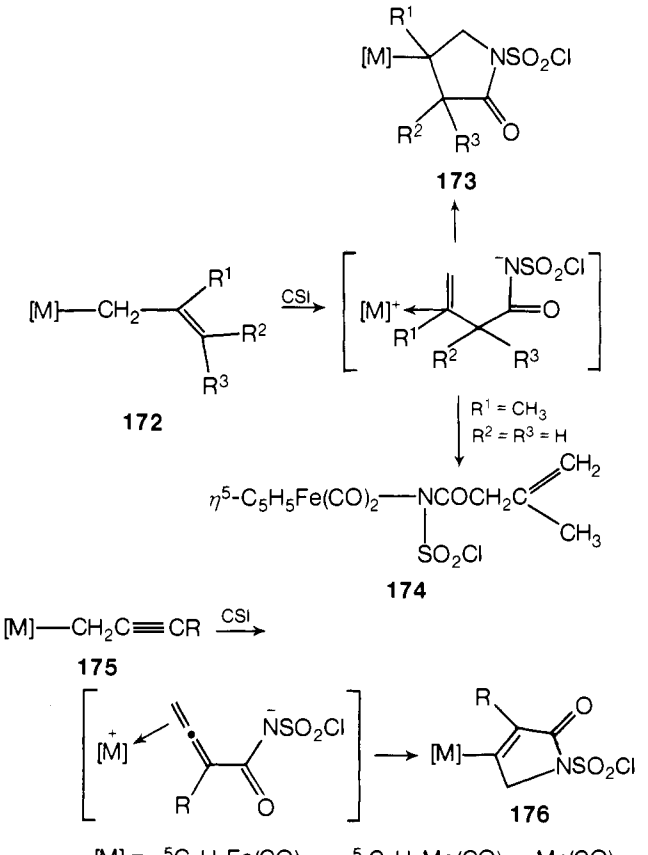
170 171

(60)

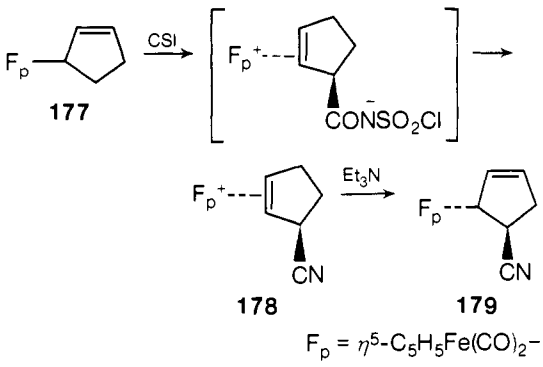
E. Metal-Assisted (3 + 2) Cycloadditions

Transition metal-2-alkenyl (**172**) and -2-alkynyl (**175**) complexes undergo extremely facile (3 + 2) cycloadditions with CSI. These reactions take place with 1,2 metal migration and lead to pyrrolidones **173** and Δ^3-pyrrolinones **176**, respectively (Scheme XXII).[65,66] In one case, however, the apparent insertion product **174** was obtained.[65b,c] The cyclic complex **177** does not undergo cycloaddition, but rather forms **178**, deprotonation of which yields **179**.[66] The formation of **178** probably takes place via a pathway similar to that which was described in section II.A for the conversion of amides **6** into nitriles **7**.

SCHEME XXII



[M] = η^5-$C_5H_5Fe(CO)_2$–, η^5-$C_5H_5Mo(CO)_3$–, $Mn(CO)_5$–



177 178 179

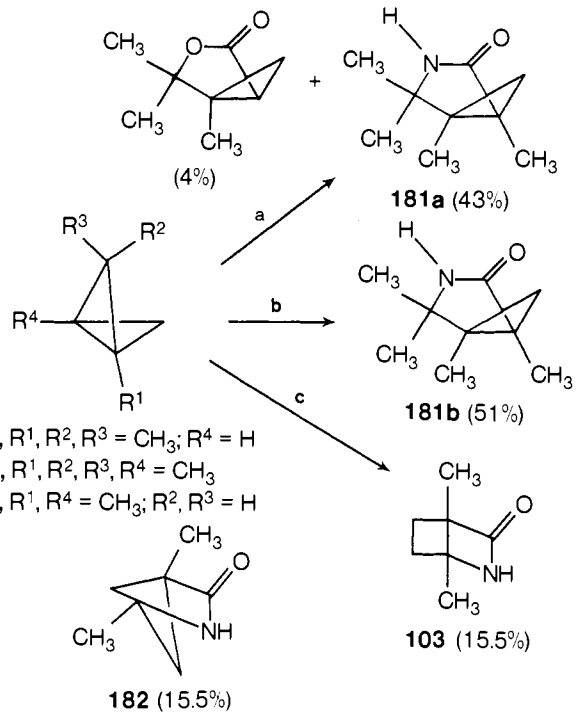
$F_p = \eta^5$-$C_5H_5Fe(CO)_2$–

(61)

F. Bicyclo[1.1.0]butanes

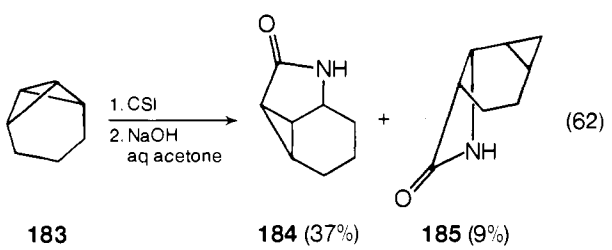
Although no multiple bond is involved, the cycloaddition of CSI to bicyclobutanes is classified as a type II reaction, mainly because of the high degree of π character in the σ bonds of these highly strained bicyclic hydrocarbons and because of the overall similarity of this reaction to that with olefins. The methyl-substituted bicyclobutanes **180** react with CSI to produce, following hydrolysis, the products shown in Scheme XXIII.[45] The structure of **103** was previously[45a] reported to be

SCHEME XXIII



180a, $R^1, R^2, R^3 = CH_3$; $R^4 = H$
b, $R^1, R^2, R^3, R^4 = CH_3$
c, $R^1, R^4 = CH_3$; $R^2, R^3 = H$

182. In addition, tricyclo[4.1.0.$0^{2,7}$]heptane (**183**) produces lactams **184** and **185.** The results can be rationalized[45] as



183 184 (37%) 185 (9%)

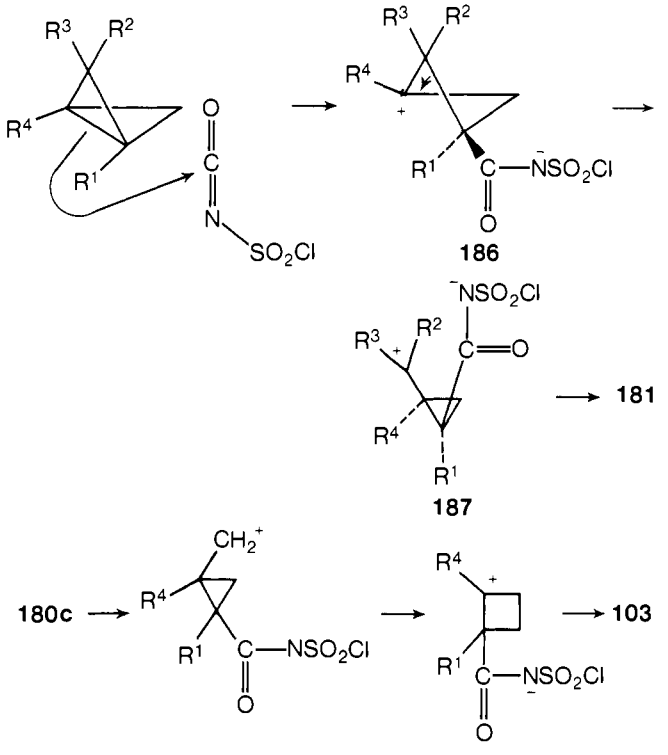
(62)

initial bonding to C_1 in S_E2-like fashion from below the edge of the flap to produce cyclobutyl carbonium ion **186.** When substituents R^2 and R^3 are aiding in the stabilization of a positive charge, rearrangement to cyclopropylcarbinyl cation **187** occurs prior to ring closure to **181.** The formation of **103** may be due to a double Wagner-Meerwein rearrangement of **186,**

TABLE IX. 2-Chloroalkanesulfonyl Isocyanates 192 from Olefins and CSI

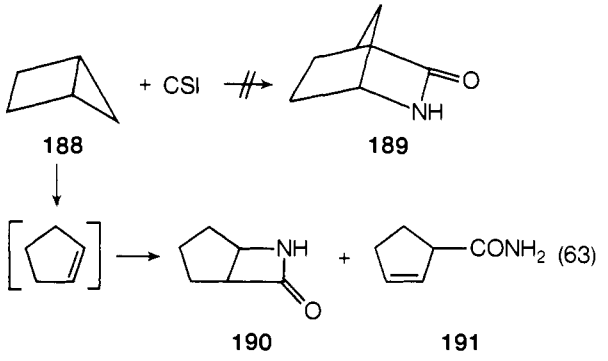
Olefin	R^1	R^2	% yield
Ethylene	H	H	84
Propene	CH_3	H	90
1-Butene	CH_3CH_2	H	70
2-Butene	CH_3	CH_3	92
1-Hexene	C_4H_9	H	63
Cyclohexene	$-(CH_2)_4-$		50
Allyl chloride	$ClCH_2$	H	73
Vinyl chloride	Cl	H	11
Vinyl chloride	Cl_2CHCH_2	H	60
Vinyl chloride	$Cl_2CHCH_2CHClCH_2$	H	3

SCHEME XXIV



or more likely via edge-bond cleavage in **180c** followed by rearrangement to a cyclobutyl cation and cyclization. Isomerization of **180c** to 1,2-dimethylcyclobutene prior to cycloaddition has also been considered.

Initial assignments[45,67] of the 2-azabicyclo[2.2.1]heptan-3-one (**189**) structure to the product from bicyclo[2.1.0]hep-



(63)

tane (**188**) and CSI have recently been shown to be in error.[68] In the case of **188** the cycloadduct is actually β-lactam **190**, produced by CSI-induced isomerization of **188** to cyclopentene (a known process in CSI–cyclopropane reactions[3]) followed by normal (2 + 2) cycloaddition. Cyclopentene-3-carboxamide (**191**) is also produced in this reaction.

TABLE X. Isothiazolidine 1,1-Dioxides 193 from Olefins and CSI

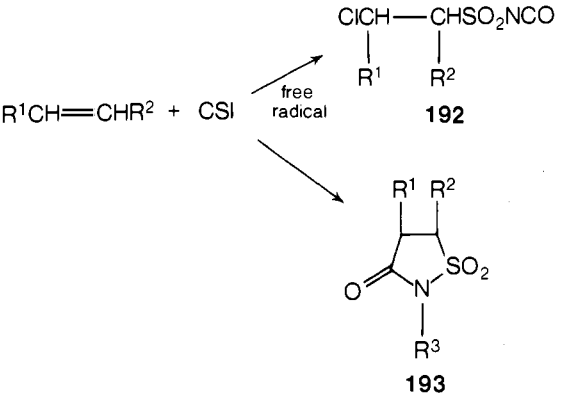
Olefins	R^1	R^2	R^3	% yield
Ethylene	H	H	$-CH_2CH_2Cl$	75
Propene	CH_3	H	$-CH_2C(CH_3)Cl$	80
2-Butene	CH_3	CH_2	$-CH(CH_3)CH(CH_3)Cl$	60
1-Hexene	C_4H_9	H	$-CH_2CHClC_4H_9$	62
Cyclohexene	$-(CH_2)_4-$		2-Cl-c-C_6H_{10}	50

IV. Reactions of Type III Involving the Chlorosulfonyl Group

Reactions with the chlorosulfonyl group of CSI may occur with compounds that cannot react with the isocyanate function, or under special conditions.

A. Olefins

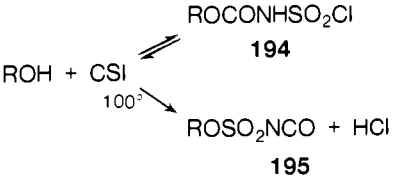
Under free radical conditions (radical initiators or ultraviolet irradiation), CSI undergoes a type III reaction with olefins to produce 2-chloroalkanesulfonyl isocyanates **192** in good yield (Table IX).[69] By changing the reaction conditions, the course of the reaction is changed dramatically and 2-(2-chloroalkyl)-3-oxoisothiazolidine 1,1-dioxides (**193**) are produced (Table X).



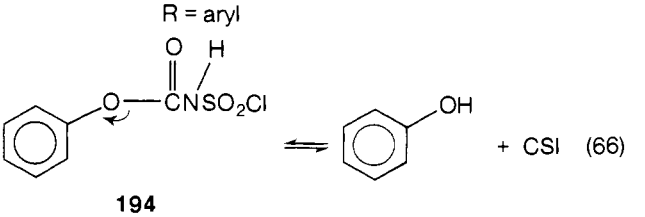
(64)

B. Alcohols and Phenols

Reaction of CSI with phenols at room temperature or slightly elevated temperatures produces the normal type I products, namely, carbamates **194**. Above about 100 °C, however, this reaction is reversible, and a new type III reaction sets in, producing aryloxysulfonyl isocyanates **195**.[70]



(65)



(66)

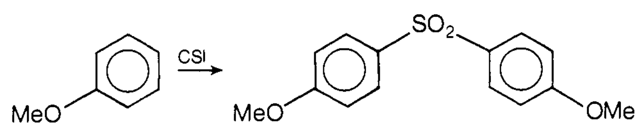
This reaction is not directly applicable to normal alcohols since formation of carbamate **194** (R = alkyl) is not reversible under these conditions. The reason for the more facile reversibility of **194** (R = aryl) is that ArO^- is a better leaving

$$\underset{\mathbf{194}}{ArOCONHSO_2Cl} \xrightarrow{ROH} \underset{\mathbf{196}}{ArOCONHSO_2OR} \xrightarrow{\Delta} \underset{\mathbf{195}}{ROSO_2NCO} + ArOH \quad (67)$$

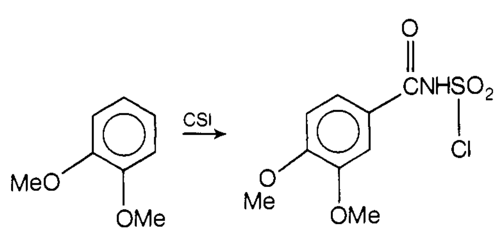
group than RO⁻ (R = alkyl). The problem is easily overcome, however, by preparing an arylurethane **194** (R = aryl) which on reaction with an alcohol gives **196.** Thermal decomposition of the latter produces the alkoxysulfonyl isocyanate **195** (R = alkyl),[71] in good to excellent yields.

C. Phenolic Ethers

An unusual type III reaction occurs between CSI and anisole,[72] the only product isolated being bis(4-methoxyphenyl) sulfone (**197**). More highly substituted phenolic ethers usually undergo reaction with the isocyanate function (see below).[2] Chlorination of a phenol ether has also been reported (see section V).[73]



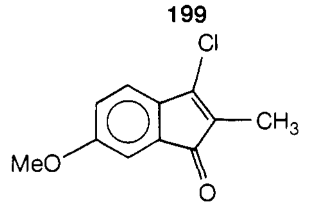
197 (68)



(69)

Unusual results were obtained in the reaction of p-methoxypropiophenone (**198**) with CSI.[14] Only 3% of oxathiazine dioxide **28** (R^1 = $CH_3OC_6H_9$) (R^2 = CH_3) was isolated (Table II), and instead ethyl p-methoxypropiophenone-α-sulfonate (**199**) as well as 3-chloro-6-methoxy-2-methylindenone (**200**) were obtained in 40 and 7% yields, respectively.

$$\underset{\mathbf{198}}{p\text{-}MeOC_6H_4C(=O)CH_2CH_3} \xrightarrow{CSI} \underset{\mathbf{199}}{p\text{-}MeOC_6H_4C(=O)CH(CH_3)SO_2OEt} +$$



(70)

200

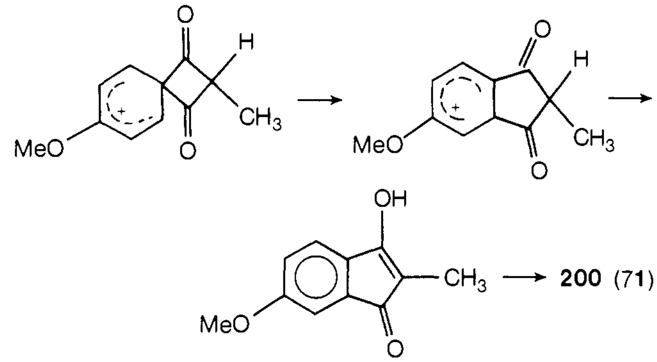
While **199** arises from a reaction of type III with involvement of the solvent (diethyl ether), the formation of **200** is rationalized via the primary adduct **201** as shown in eq 71.

D. Other Examples

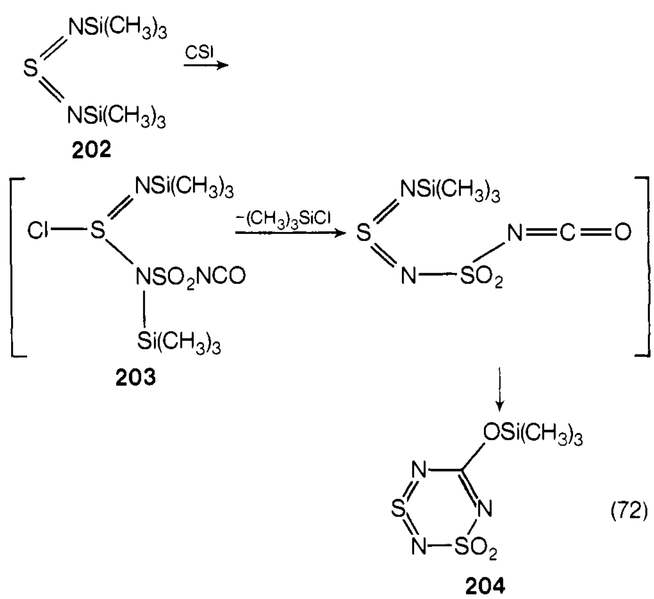
CSI has been reported to react with sulfur bis(trimethylsilyl)diimide (**202**) producing **204** (eq 72).[74] The first step could be a type III addition to the S=N bond to give **203** followed by elimination of trimethylsilyl chloride and cyclization.

Unlike sulfonamides derived from ammonia which react with the isocyanate function (section II.A), those derived from primary amines have been reported[75] to undergo reaction with the sulfonyl group of CSI to form **205.** Presumably, the

$$\mathbf{198} \longrightarrow \underset{\mathbf{201}}{p\text{-}MeOC_6H_4C(=O)CH(CH_3)C(=O)NHSO_2Cl} \longrightarrow$$



(71)



(72)

product is formed in an addition-elimination sequence similar to that discussed above for phenols.

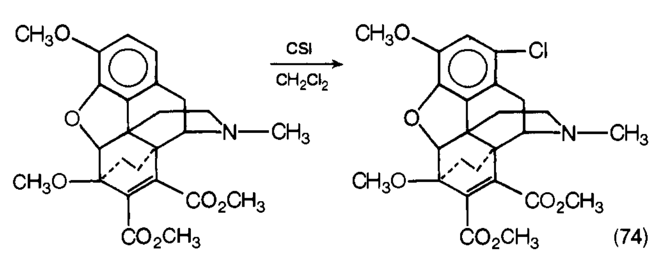
$$RSO_2NHR^1 + CSI \longrightarrow \underset{\mathbf{205}}{RSO_2N(R^1)SO_2NCO} \quad (73)$$

R^1 = alkyl and cycloalkyl

V. Unusual and Divergent Reactions

A. Chlorination

In an unique example, CSI has been found to function as a chlorinating agent upon the phenolic ether **206**, producing **207** in 81% yield.[73]

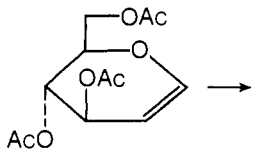


(74)

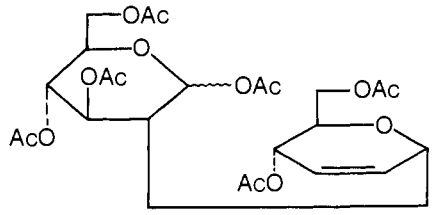
206 **207**

B. Unsaturated Sugars

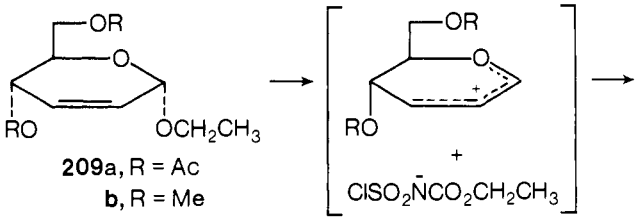
Attempts to add CSI to unsaturated sugars has produced some unusual results.[76] CSI functions only as a Lewis acid upon **208**, catalyzing its dimerization. With sugars **209a** and **209b**, the major products **210** can be rationalized as deriving



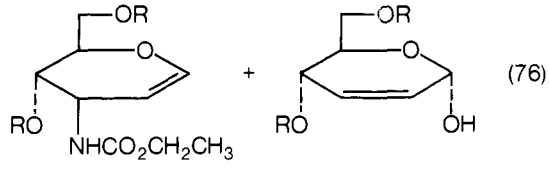
208



(75)



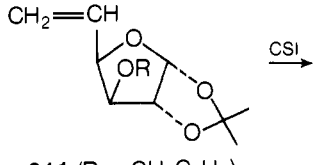
209a, R = Ac
b, R = Me



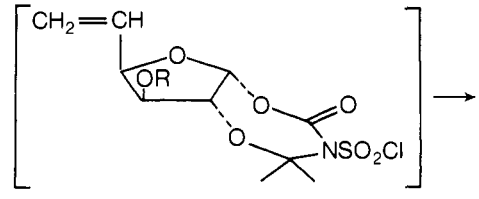
(76)

210a (60%)
b (33%)

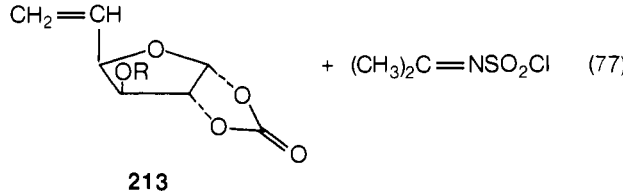
from initial abstraction of the anomeric ethoxy group by CSI acting as an electrophile, in a manner similar to the one described for acetals (section II.B). Reaction of **211** with CSI produces **213** in 40% yield. The type I product **212** may be an intermediate. This reaction could not be extended into a general synthesis of 1,2-carbonate compounds.



211 (R = $CH_2C_6H_5$)



212



(77)

213

VI. Addendum

A. Reactions of Type I

N-Chlorosulfonyl-*N'*-(dialkyl- and -diarylsulfamoyl)ureas ($R^1R^2NSO_2NHCONHSO_2Cl$; R^1, R^2 = CH_3, C_2H_5, C_6H_5, $-CH_2-$, $-(CH_2)_2O(CH_2)_2-$) have recently been prepared by reaction of *N,N*-dialkyl- or *N,N*-diarylsulfamides with CSI.[77] Hydrolysis with aqueous ethanol produces ureas $R^1R^2NSO_2NHCONH_2$ in high yield, while pyrolysis produces the corresponding sulfamoyl chlorides $R^1R^2NSO_2Cl$ via the possible intermediacy of sulfamoyl isocyanates.

B. Reaction of Type II

Recent results with vinylsilanes[78] once again illustrate the fine line separating type I and type II products in the reaction of CIS with multiple bonds. Whereas low-temperature reaction and hydrolysis provides a β-lactam from **1**,1-dimethyl-2,5-diphenyl-**1**-silacyclopenta-2,4-diene, room-temperature reaction affords a silacycloheptane derivative. Similarly, *trans*-β-trimethylsilylstyrene produces an imidate in 92% yield (essentially a type I product) via silicon migration from carbon to oxygen in the zwitterionic intermediate.

Methano[10]annulene, when treated with CSI followed by hydrolysis, affords low yields of type I products. Direct ir observation of the reaction mixture at low temperature suggested the presence of a β-lactam, which underwent rearrangement upon warming.[79]

Homobarrelene, upon reaction with CSI, affords four different cyclic products, the ratios of which change with reaction time. The formation of these products is rationalized to occur by electrophilic attack at the anti double bond with a strong preference for endo approach. By contrast, *syn*-benzohomobarrelene undergoes reaction preferentially from the exo direction, and *anti*-benzohomobarrelene is unreactive toward CSI.[80]

Recent work reports that reaction of CSI with bisected vinylcyclopropanes produces seven-membered lactams. The intermediacy of β-lactams could not be detected spectroscopically, thus suggesting either a zwitterionic intermediate or a near-concerted 2a + 4a type cycloaddition.[81]

CSI also undergoes 2 + 4 cycloaddition with acetyl isocyanate producing 3-chlorosulfonyl-6-methyl-2*H*-**1**,3,5-oxadiazine-2,4(3*H*)-dione in 40% yield.[84]

A detailed study utilizing model compounds should allow accurate assignments to be made to reaction products of polyisoprene and CSI.[79] The compounds $C_2H_5(H_2C(CH_3)=CHCH_2)_nC_2H_5$ (*n* = **1** and 2) were chosen as models for **1**,4-polyisoprene, while $CH_2=C(CH_3)CH(C_2H_5)_2$ was the model for 3,4-polyisoprene. The products obtained indicate that the reaction may be more complicated than previously reported.[43,44] A mechanistic rationale is provided[79] which may have implications for other CSI–olefin interactions as well.

Tetrasulfur tetranitride is reported to yield monoaddition products with CSI and related isocyanates in near-quantitative yield.[83] The products, believed to be **1**,4-adducts, thermally revert to starting materials.

C. Reactions of Type III

In analogy to the formation of **204** from *N,N'*-bis(trimethylsilyl)sulfur diimide, the corresponding sulfoxide is produced by reaction of CSI with bis(trimethylsilylimido) sulfoxide.[85]

Note. Since we undertook the writing of this review article, chlorosulfonyl isocyanate has become commercially unavailable except at a near-prohibitive price (E. G. Tridom Chemical, Inc., Hauppauge, N.Y., $40/10 ml). This unfortunate situation has discouraged new investigations into the synthetic utility of a completely unique and remarkable reagent. However, CSI can be prepared in reasonable quantities by the reaction of CNCl with sulfur trioxide.[86]

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