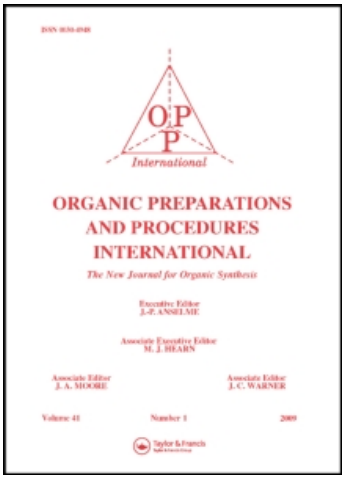

Organic Preparations and Procedures International
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t902189982

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To cite this Article Delia, Ernest W. and Lochert, Ian J.(1996) 'SYNTHESIS OF BIUDGEHEAD-SUBSTTTUTED BICYCLO[1.1.1]PENTANES. A REVIEW', Organic Preparations and Procedures International, 28: 4, 411 — 441
To link to this Article: DOI: 10.1080/00304949609356550
URL: http://dx.doi.org/10.1080/00304949609356550

ORGANIC PREPARATIONS AND PROCEDURES INT., 28 (4), 411-441 (1996)

SYNTHESIS OF BRIDGEHEAD-SUBSTITUTED BICYCLO[1.1.1]PENTANES. A REVIEW

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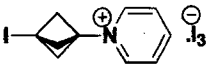
INTRODUCTION

Bicyclo[1.1.1]pentane (**1**) is a highly strained system which possesses considerable aesthetic appeal as a result of its highly-symmetrical (D_{3h}) geometry. The parent hydrocarbon has been known for *ca.* 30 years[1] and, over the intervening period, **1** and its derivatives, particularly the bridgehead-substituted bicyclo[1.1.1]pentanes, have been the focus of intense study both experimentally and computationally. One of the unusual features of the bicyclopentane system is the close proximity of the bridgehead carbons the separation of which generally falls in the range 1.80-1.91A. Indeed, the C1-C3 distance of 1.80A determined in the quaternary bicyclopentane salt **2** by X-ray structure analysis[2] represents the shortest known distance between non-bonded carbon atoms. The constraints imposed by the unique geometry of the bicyclo[1.1.1]pentane system, which necessitates a degree of overlap between the rear-lobes of the bridgehead carbon exocyclic bonding orbitals, has been suggested to have important connotations with respect to certain properties of the molecule and its derivatives.

1



2

Aside from the wide variety of studies on chemical aspects of bicyclo[1.1.1]pentane and its derivatives, considerable interest has been shown recently in **1** and its oligomers as molecular building blocks for the construction of novel materials[3-16] and as potential liquid crystals[17-19]. Incorporation of a bicyclo[1.1.1]pentyl unit into antibacterial agents has also claimed[20] to enhance the potency of the drug. The combination of all these investigations has led to an explosive expansion of the literature covering synthetic methods for bridgehead-substituted bicyclo[1.1.1]pentanes, particularly in the 1990's.

This review has been designed to cover procedures available for the synthesis of bicyclo[1.1.1]pentanes with substitution in at least one bridgehead position, with the main emphasis on the making and breaking of bonds to the bicyclo[1.1.1]pentyl bridgehead carbons. Accordingly, in the section describing the interconversion of functional groups, for example, procedures regarded as standard or trivial such as the conversion of an acid into its ester or amide or its reduction to an

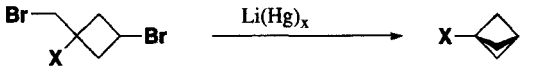
alcohol have not been included. Similarly, reduction of functional groups, viz., X→H, have been omitted. Reference to the synthesis of the oligomeric bicyclopentanes, commonly referred to as [n]staffanes (n≥2), has generally been omitted[11b]. Furthermore, although they only constitute a few examples, the preparation of 2-substituted derivatives when a bridgehead substituent is also present has been excluded when the reaction does not involve the bridgehead functionally.

I. EARLY SYNTHESES OF THE BICYCLO[1.1.1]PENTYL SYSTEM

The earlier methods devised for the synthesis of bicyclo[1.1.1]pentane (**1**) and several of its derivatives can be grouped into four categories. Although, because of their low yields, these procedures have generally been superseded by the newer techniques, there are occasions where they have been used to advantage when small quantities of material were required.

1. Intramolecular Radical Coupling

In 1964 Wiberg and his associates[1] reported the first synthesis of **1** (6% yield) via a Wurtz coupling of 3-bromomethylcyclobutyl bromide (**3**) (Eq. 1). Rifi[21] noted that the yield could be increased twofold if coupling were induced electrochemically. At the same time, it was observed[1] that use of modified cyclobutanes afforded the 1-deuterio- and 1-methyl- derivatives (**4** and **5**) in similar yield. Preparation of **4** and **5** therefore represented the first synthesis of bridgehead derivatives.



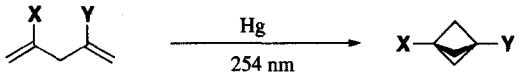
(1)

3

1, X = H
4, X = D
5, X = CH_3

2. Photocyclization

In an alternative method devised by Srinivasan and Carlough[22], mercury-photosensitized irradiation of 1,4-pentadiene (**6**) and its 2-methyl- and 2,4-dimethyl- derivatives (**7** and **8**) in the gas-phase at short wavelength UV light induced cyclization to the bicyclo[1.1.1]pentanes **1**, **5** and **9** respectively (Eq. 2). Yields of the bicyclic hydrocarbons were not reported, however.



(2)

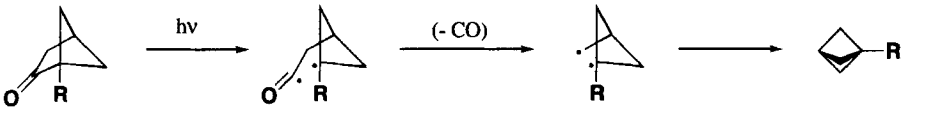
6, X = Y = H
7, X = H, Y = CH_3
8, X = Y = CH_3

1, X = Y = H
5, X = H, Y = CH_3
9, X = Y = CH_3

3. Decarbonylation of 2-Bicyclo[2.1.1]hexanones

In 1967, Meinwald and his coworkers[23] noted that the combination of photochemically-induced decarbonylation of 2-bicyclo[2.1.1]hexanone (**10**) in the gas-phase accompanied by cyclization of the diradical so produced proved to be a viable entry to the target hydrocarbon **1** (Eq. 3).

Although the yield of bicyclo[1.1.1]pentane (16-20%) was considerably improved over that obtained in the procedures described above, the main drawback of the method is the requirement for decarbonylation to be effected in the gas-phase thus limiting the scale of operation. Unfortunately, in the condensed phase ring-opened products were found to predominate[24].



(3)

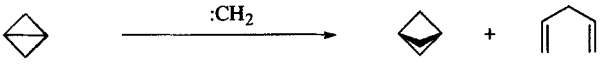
10, R = H
11, R = F
12, R = $^{13}CH_3$

1, R = H
13, R = F
14, R = $^{13}CH_3$

Nevertheless, Srinivasan[25] found this to be a convenient route to the parent **1**, and it also proved to be invaluable for the synthesis of 1-fluorobicyclo[1.1.1]pentane (**13**)[26] and 1-methylbicyclo[1.1.1]pentane-6-^{13}C (**14**)[27] from the precursor 2-bicyclo[2.1.1]hexanones **11** and **12**, respectively, in the small quantities required for NMR studies.

4. Carbene Insertion in Bicyclo[1.1.0]butanes

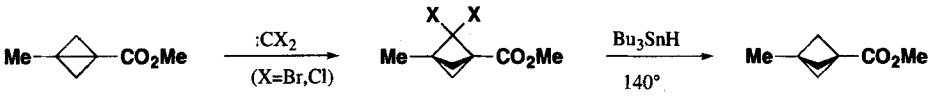
Wiberg and his colleagues[28] were the first to demonstrate that carbenes add across the strained central bond of bicyclo[1.1.0]butane (**15**) to give mixtures of bicyclo[1.1.1]pentanes and 1,4-pentadienes. In the addition of $:CH_2$, for example, **1** was produced in very small quantity (1%) accompanied by larger amounts (21%) of the isomer, 1,4-pentadiene (**16**) (Eq. 4).



(4)

15 **1** **16**

Subsequently, Hall and associates[29] discovered that the bridgehead-substituted bicyclo[1.1.1]pentanes **18** and **19** could be obtained in low yield (3-5%) by addition of the dihalocarbenes to the bicyclo[1.1.0]butyl ester **17** (Eq. 5). It was some time later, however, before Applequist and his coworkers[30,31] showed that judicious fine-tuning of the reaction conditions provided access to the bridgehead-substituted bicyclo[1.1.1]pentanes on a scale that delivered usable quantities of material. Thus, e.g., dechlorination of **18** was effected by high-temperature treatment with Bu_3SnH affording the ester **20** in 15% yield overall from **17**.



(5)

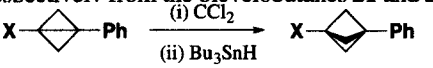
17

18, X = Cl
19, X = Br

20

In a similar way, Applequist[30,31] synthesised the synthetically valuable intermediates **23** and

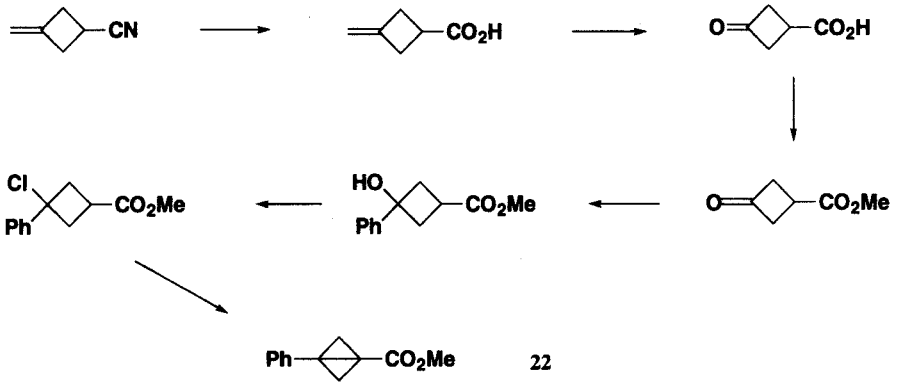
24 in yields of 10% and 40% respectively from the bicyclobutanes **21** and **22** (Eq. 6).



(6)

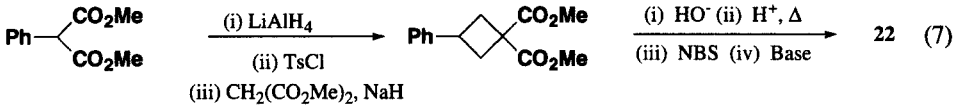
21, X = CN
22, X = CO_2CH_3
23, X = CN
24, X = CO_2CH_3

The complete route for the synthesis of the ester **22** is depicted in Scheme 1.



Scheme 1

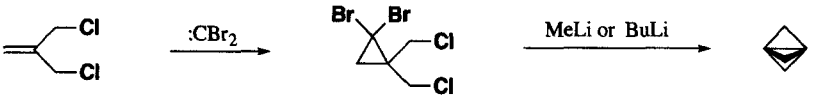
Although the sequence illustrated in Scheme 1 is rather low-yielding and time-consuming, nevertheless for several years it represented the only really practical route to bridgehead-substituted bicyclo[1.1.1]pentanes in quantity. A useful modification (Eq. 7) leading to the bicyclic ester **22** was introduced by the Wiberg group[32] and was employed[32-35] with considerable success to access several bridgehead-substituted bicyclo[1.1.1]pentanes.



(7)

II. MODERN STRATEGY FOR CONSTRUCTION OF THE BICYCLO[1.1.1]PENTYL SYSTEM: RING OPENING OF [1.1.1]PROPELLANE

Without exception, the favored precursor nowadays for the preparation of a wide variety of bridgehead-substituted bicyclo[1.1.1]pentanes is [1.1.1]propellane (**27**), which was first synthesised by Wiberg and Walker[33] in 1982. The route to **27** employed currently was devised by Szeimies and colleagues[3] and involves dibromocarbene addition to commercially-available 3-chloro-2-chloromethylpropene (**25**) to give the tetrahalide **26** followed by treatment of the latter with an alkyllithium (Eq. 8). An improved version was subsequently reported[36] including a description for the preparation and purification of solvent-free [1.1.1]propellane[37]. Modifications[38,39] have also been introduced leading to higher yields of the tetrahalide **26** which is now also commercially available.

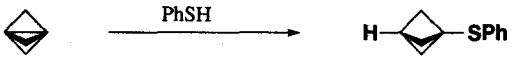


(8)

25 26 27

1. Ring Opening Mediated by Radicals

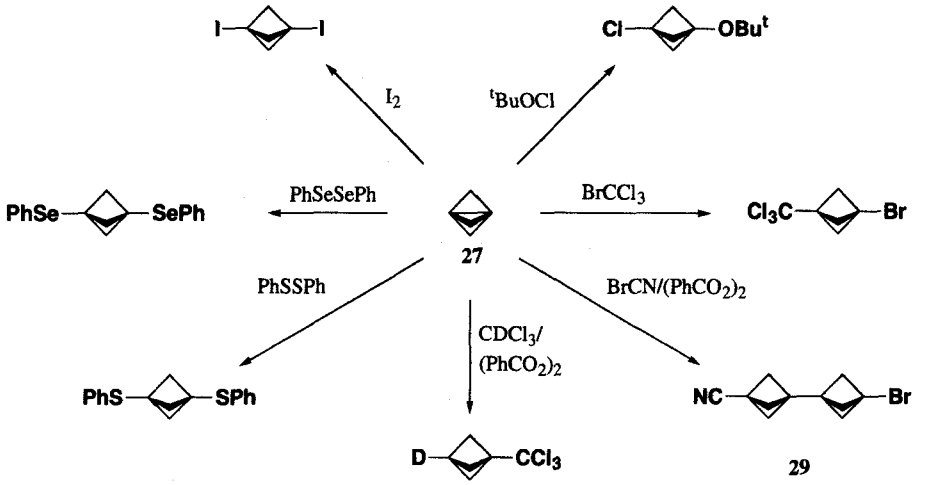
Szeimies and his colleagues[36] were the first to report that the reaction of radicals with [1.1.1]propellane was a very effective way to generate bicyclo[1.1.1]pentanes with substitution at the bridgehead; thus, the radical-induced ring-opening of **27** by thiophenol gave the thioether **28** in 34% yield (Eq. 9). This type of reaction provides the basis for essentially all the procedures now employed for the synthesis of bridgehead-substituted bicyclo[1.1.1]pentanes via radical intermediates. It represents, by far, the most popular mode of fission of [1.1.1]propellane and, as shown below, it has been exploited very successfully principally by the Wiberg and Michl groups. Interestingly, these transformations are mediated by bicyclo[1.1.1]pentyl bridgehead radicals which, unlike the corresponding bridgehead cations, possess considerable thermodynamic and kinetic stability[40].



(9)

27 28

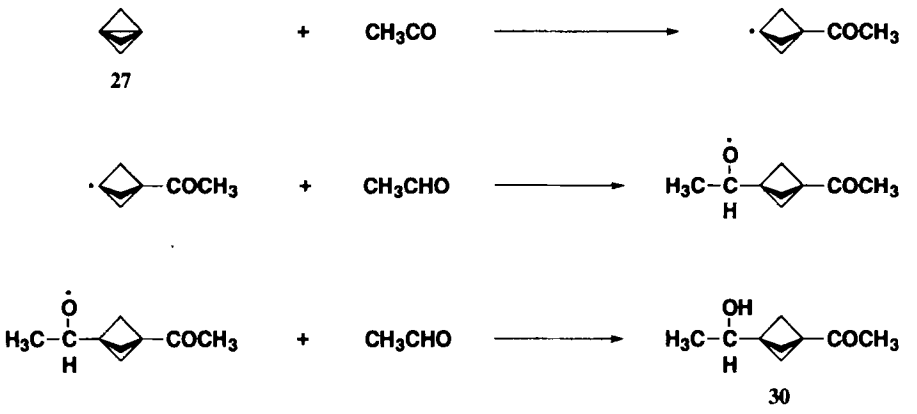
Soon after the discovery by Szeimies and associates[36], Wiberg, Waddell and Laidig[41] described the reactive nature of [1.1.1]propellane towards radicals in general. A summary of their observations is depicted in Scheme 2.



Scheme 2

Two aspects of these conversions are noteworthy: (a) the reaction of **27** with cyanogen bromide gave the adduct **29** as the major product, and (b) the benzoyl peroxide-catalyzed addition of

acetaldehyde to **27** proceeded to give the 2:1 adduct **30** in a chain-carrying process (Scheme 3) which is not the normally-accepted mode of addition.



Scheme 3

An enormous number of radical-induced ring-opening reactions of [1.1.1]propellane leading to mono- and di-substituted bicyclo[1.1.1]pentanes have been recorded since 1984; these are collected in Table 1. Inspection of the data reveals that some of the examples have minimal impact as useful synthetic procedures. For example, in some cases yields are low owing to the concomitant formation of higher, oligomeric staffanes, while in others complex mixtures of substituted bicyclo[1.1.1]pentanes are obtained particularly when diethyl ether is used as solvent and becomes incorporated into the bicycloalkane. Furthermore, although most operations can be performed on crude [1.1.1]propellane without requiring its isolation prior to use, some of the additions are found to be successful only when the propellane has been purified. Notwithstanding these limitations, the majority of the radical additions are seen to lead to good yields of desired products.

Arguably, the key reaction and single most important synthesis of all those leading to bridgehead-substituted bicyclo[1.1.1]pentanes collected in Table 1 is the addition of biacetyl to [1.1.1]propellane to give 1,3-diacetylbicyclo[1.1.1]pentane (**31**) (entry 67). This transformation was first reported by Kaszynski and Michl[57]. The reaction is relatively easy to perform, it proceeds in good yield, and it delivers a product which is of reasonable purity. This conversion is highly significant because, as discussed later in connection with the interconversion of bridgehead functional groups, the derived diacid **32** (Eq. 10) is the natural precursor to a huge number of asymmetrically-substituted bicyclo[1.1.1]pentane derivatives[34,38,45,49,55] owing to the unique versatility of the carboxyl group to manipulation. This is achieved from the half ester **34** which can be prepared in high yield by selective hydrolysis of the diester **33**.

(10)

27 **31**

32, X = Y = H
33, X = Y = Me
34, X = H, Y = Me

Table 1. Synthesis of Bridgehead-Substituted Bicyclo[1.1.1]pentanes by Radical-Induced Opening of [1.1.1]Propellane.

Entry	Co-Reactants X—Y	Conditions	X	Y	Yield (%)	Ref
1	I_2	Et_2O/pentane, hν, -20°	I	I	67[a]	37
2	I_2	Et_2O/pentane, rt	I	I	88[a]	41,42
3	I_2	Et_2O/pentane	I	I	42[a]	10
4	I_2	Et_2O/pentane	I	I	nr[b]	43
5	I_2	Et_2O/hexane, rt	I	I	100	44
6	CH_2=$CHCH_2I$	Et_2O/pentane, hν, 1 hr, rt	I	I	10[a]	45
7	Br_2	Et_2O/pentane, hν, -25°	Br	Br	36[a]	38
8	Br_2	Et_2O/pentane	Br	Br	13[a]	10
9	Br_2	Et_2O/pentane, hν, 10 min, -15°	Br	Br	37	44
10	$PPh_3/(CCl_2Br)_2$	hν	Br	Br	31[c]	46
11	CH_3I	Et_2O, hν, 30 min, 0°	I	Me	68	47
12	CH_3I	hν, 24 hrs, -30°	I	Me	42	48
13	CH_3I	pentane, hν, 30 min, rt	I	Me	65	44
14	$^{13}CH_3I$	pentane/Et_2O, hν, 75 min, rt	I	^{13}Me	60	49
15	CH_2Cl_2	Et_2O/CH_2Cl_2, hν, 13 hrs, rt	H	$CHCl_2$	44[c]	50
16	$CHCl_3$	$Et_2O/CHCl_3$, hν, 16 hrs, rt	H	CCl_3	81	50
17	$CHCl_3$	hν, 40 min, 10°	H	CCl_3	70	51
18	$CHCl_3$	pentane, hν, 30 min, 0-10°	H	CCl_3	70[c]	44
19	$CDCl_3$	hν, 15 min, rt	D	CCl_3	43[c]	41,42
20	$^{12}CDCl_3$	hν, 60 hrs, rt	D	$^{12}CCl_3$	13	50
21	$CHCl_2I$	Et_2O/CH_2Cl_2, hν, 16 hrs, rt	I	$CHCl_2$	96	50
22	$^{12}CHCl_2I$	Et_2O/CH_2Cl_2, hν, 16 hrs, rt	I	$^{12}CHCl_2$	41	50
23	CBr_4	Et_2O/pentane	Br	CBr_3	nr	43
24	CBr_4	hexane, hν, 1 hr, 20°	Br H	CBr_3 CBr_3	83 8	44
25	CCl_4, $(t\text{-BuO})_2$	hν, 1 hr, rt	Cl	CCl_3	79	42
26	CCl_4	hν, 40 min, 10°	Cl	CCl_3	72	51
27	CCl_4	hν, 30 min, rt	Cl	CCl_3	70[c]	44
28	$CHBr_3$	Et_2O, hν	Br	$CHBr_2$	93	50
29	$CHBr_3$	hexane, hν, 1.5 hr, 20°	Br	$CHBr_2$	88	44
30	CF_3I	Et_2O, 3 days, rt	I	CF_3	75	52

Table 1. Continued

Entry	Co-Reactants X—Y	Conditions	X	Y	Yield (%)	Ref
31	Br_2CF_2	pentane, hv, 1 hr, rt	Br	CF_2Br	85[c]	53
32	$BrCCl_3$	$CDCl_3$, hv, 1 hr	Br	CCl_3	nr	41,42
33	$PhICl_2$, $CHCl_3$	Et_2O/pentane, hv, 12 hrs, 0-20°	I	CCl_3	23	44
34	$MeCH_2I$	Et_2O, hv, 30min, 0°	I	CH_2Me	90	47
35	$MeCHCl_2$	hv, 24 hrs, -30°	H	CCl_2Me	21[ac]	48
36	$MeCCl_3$	hv, 24 hrs, -30°	Cl	CCl_2Me	18[ac]	48
37	$BrCF_2CF_2Br$	pentane, hv, 2 hrs, rt	Br	CF_2CF_2Br	40[b]	53
38	$Me(CH_2)_3I$	Et_2O/pentane, hv, 5 hrs, rt	I	$(CH_2)_3Me$	34[a]	10
39	*t*-BuBr, $(PhCO)_2O$	Et_2O/pentane, hv, 5 hrs, rt	Br	*t*-Bu	16[a,c]	10
40	*t*-BuBr, $(PhCO)_2O$	hv, 80°	Br	*t*-Bu	36	46
41	*t*-BuOCl	-78°→rt, 4 hrs	Cl	*t*-BuO	57	41,42
42	MeCH(I)Et	Et_2O/pentane, hv, 5 hrs	I	CH(Me)Et	32[a]	10
43	PhI	Et_2O/pentane, hv, 18 hrs, rt	I	Ph	nr[c]	10
44	PhI	Et_2O/pentane, hv, 5 hrs, rt	I	Ph	nr[c]	38
45	4-$MeOC_6H_4I$	Et_2O/pentane, hv, 5 hrs, rt	I	4-$MeOC_6H_4$	nr[c]	38
46	$PhCH_2Br$	Et_2O/pentane, hv, 10 hrs, rt	Br	CH_2Ph	32[a,c]	10
47	$BrCH(COOMe)_2$	Et_2O/pentane, hv, 2 hrs, 10-15°	Br	$CH(COOMe)_2$	68[c]	44
48	Ph_3SnH, $(t\text{-BuO})_2$	Et_2O, hv, 1 hr, rt	H	$SnPh_3$	68	54
49	Ph_3SnH, AIBN	Et_2O/pentane, hv, 40 min, rt	H	$SnPh_3$	73	55
50	$(C_6H_{11})_3SnH$, $(t\text{-BuO})_2$	Et_2O, hv, 1 hr, rt	H	$Sn(C_6H_{11})_3$	63	54
51	Me_3SnH, $(t\text{-BuO})_2$	Et_2O, hv, 0.5 hr, rt	H	$SnMe_3$	59	54
52	Bu_3SnH	Et_2O, hv, 6 hrs, 20-25°	H	$SnBu_3$	28	44
53	Bu_3SnH, (t-BuO)$_2$	Et_2O, hv, 1 hr, rt	H	$SnBu_3$	60[a]	54
54	Bu_3SnH, AIBN	Et_2O/pentane, hv, 40 min, rt	H	$SnBu_3$	52	55
55	Bu_3SnD, AIBN	Et_2O/pentane, hv, 40 min, rt	D	$SnBu_3$	49	49
56	$NO/NO_2/CS_2$	CS_2, -78°→ rt, 30 min	NO_2	SCN	90	42
57	N_2O_4	Et_2O, 15 min, rt	NO_2	NO_2	25	42
58	N_2O_4	Et_2O, 15 min, rt	NO_2 H	NO_2 NO_2	16.5 8.7	56
59	PhSH	Et_2O/pentane, hv, 10 min	H	PhS	98[a]	42
60	PhSH	Et_2O/pentane	H	PhS	34	3
61	$(PhS)_2$, AIBN	Et_2O, 4 hrs, 80°	PhS	PhS	63[c]	4
62	$(PhS)_2$	Et_2O/hexane, hv, 4 hrs,	PhS	PhS	45	41,42
63	$(MeS)_2$, AIBN	Et_2O, 4 hrs, 80°	MeS	MeS	50[c]	4

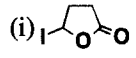
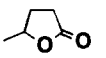
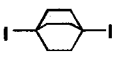
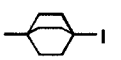
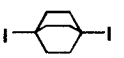
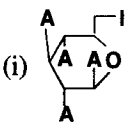
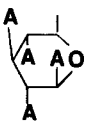
Table 1. Continued

Entry	Co-Reactants X—Y	Conditions	X	Y	Yield (%)	Ref
64	$(EtS)_2$, AIBN	Et_2O, 4 hrs, 80°	EtS	EtS	18[c]	4
65	$(EtO_2CCH_2CH_2S)_2$ AIBN	Et_2O, 4 hrs, 80°	EtO_2CCH_2-CH_2S	EtO_2CCH_2-CH_2S	18[c]	4
66	$(PhSe)_2$	Et_2O/pentane, hv, 16 hrs	PhSe	PhSe	38	42
67	$(MeCO)_2$	Et_2O/pentane, hv, 16 hrs, 0°	MeCO	MeCO	58[a]	57
68	$(MeCOS)_2$	Et_2O, hv, 6 hrs, rt	MeCOS	MeCOS	3[c]	42
69	$HPPh_2$, (*t*-BuO)$_2$	CH_2Cl_2, hv, 15 min, rt	H	PPh_2	nr	42
70	(i) $HPPh_2$, (*t*-BuO)$_2$, (ii) O_2	(i) CH_2Cl_2, hv, 15 min, rt	H	$P(Ph)_2O$	nr	42
71	$HP(O)(OMe)_2$, (*t*-BuO)$_2$	hv, 15 min, rt	H	$P(OMe)_2O$	58	42
72	NEt_3, (*t*-BuO)$_2$	hv, 15 min, rt	H	$CH(Me)NEt_2$	22	42
73	Et_3SiH, (*t*-BuO)$_2$	hv, 15 min, rt	H H	$SiEt_3$ $CH(Me)SiEt_2$	40[d]	42
74	$[(EtO)_2P]_2$, air	Et_2O, hv, 8 hrs, rt	$OP(OEt)_2$	$OP(OEt)_2$	19[a]	10
75	MeCHO, $(PhCO)_2O$	Et_2O/pentane, hv, 6 hrs, 0°	MeCO	CH(Me)OH	78[a]	57
76	MeCHO, (*t*-BuO)$_2$	hv, 15 min, rt	MeCO	CH(Me)OH	52	41,42
77	PhCHO, Et_2O	Et_2O, hv, 1.5 hrs, rt	CH(Ph)OH CH(Ph)OH	CH(Me)OEt COPh	nr nr	10
78	PhCHO, (*t*-BuO)$_2$	hv, 15 min, rt	CH(Ph)OH	COPh	49	42
79	*t*-BuCHO, (*t*-BuO)$_2$	hv, 15 min, rt	H CHO	*t*-Bu *t*-Bu	nr nr	42
80	$Me(CH_2)_2CHO$, (*t*-BuO)$_2$	hv, 15 min, rt	H CH(OH)-$(CH_2)_2Me$	$CO(CH_2)_2Me$ $CO(CH_2)_2Me$	19 50	42
81	Me_2CHCHO, (*t*-BuO)$_2$	hv, 15 min, rt	H H $CHMe_2$ $C(Me)_2CHO$ $COCHMe_2$	CMe_2CHO $COCHMe_2$ $CH(OH)CMe_2$ $CH(OH)CMe_2$ $CH(OH)CMe_2$	nr nr nr nr nr	42
82	MeCOMe, (*t*-BuO)$_2$	hv, 15 min, rt	H	CH_2COMe	33[c]	42
83	$MeCOCH_2Me$, (*t*-BuO)$_2$	hv, 15 min, rt	H	CH(Me)COMe	72	42
84	HCOOMe, (*t*-BuO)$_2$	hv, 15 min, rt	H	COOMe	40	42
85	HCOOMe, (*t*-BuO)$_2$	Et_2O,hv, 15 min, rt	H	COOMe	6.3[c]	10
86	$MeCH_2COOMe$, (*t*-BuO)$_2$	hv, 15 min, rt	H	CH(Me)-COOMe	45[c]	42

Table 1. Continued

Entry	Co-Reactants X—Y	Conditions	X	Y	Yield (%)	Ref
87	$MeCOCH_2COOMe$, $(t\text{-}BuO)_2$	hν, 15 min, rt	H	CH(COMe)-COOMe	45	42
88	$NCCH_2CH_2COOMe$, $(t\text{-}BuO)_2$	hν, 15 min, rt	H	CH(CN)-COOMe	45	42
89	$ClCH_2COOMe$, $(t\text{-}BuO)_2$	hν, 15 min, rt	H	CHClCOOMe	75	42
90	ClCH(Me)COOMe, $(t\text{-}BuO)_2$	hν, 15 min, rt	H	C(Me)Cl-COOMe	65	42
91	 , $(t\text{-}BuO)_2$	hν, 15 min, rt	H		nr	42
92	 , $(t\text{-}BuO)_2$	hν, 15 min, rt	H		12	42
			H		38	
93	MeCOCOOMe, Et_2O	Et_2O, hν, 3 hrs, rt	CH(Me)OEt CH(Me)OEt	CMe(OH)Ac CMe(OH)Ac	48[ade]	10
94	PhCOCOMe	Et_2O, hν, 3 hrs, rt	COPh COPh	$COCH_3$ COPh	24[a] 11[a]	10
95	PhCOCOPh	Et_2O, hν, 5 hrs, rt	H COPh	COPh CH(Me)OEt	nr	10
96	$(PhCO)_2O$	Et_2O, hν, 5 hrs, rt	H	CH(Me)OEt	20[ac]	10
97	SO_2Cl_2	pentane, hν, 1 hr	Cl	SO_2Cl	20	58
98	$MeSO_2Cl$	pentane, hν, 1 hr	Cl	SO_2Me	15	58
99	$MeSO_2Cl$, $(PhCO)_2O$	Et_2O/pentane, hν, 3 hrs, 0°	Cl	SO_2Me	3	10
100	$PhSO_2Cl$, $(PhCO)_2O$	Et_2O/pentane, hν, 3 hrs, 0°	Cl	SO_2Ph	51	10
101	$MeC_6H_4SO_2Cl$	pentane, hν, 1 hr	Cl[f]	$SO_2C_6H_4Me$	19	58
102	$C_6H_5CH_2OP(OMe)_2$, BPMDA[g]	C_6D_6, hν, 1 hr, 0°	$C_6H_5CH_2$	$PO(OMe)_2$	45	59
103	(i) $BrCH(COOEt)_2$; (ii) Bu_3SnH	(i)Et_2O, hν, 3 hrs, 0°; (ii) PhH, 3 hrs, 80°	H	$CH(COOEt)_2$	42[a]	45
104	(i)$BrCH_2COOMe$, (ii) Bu_3SnH	(i)Et_2O, hν, 3 hrs, 0°; (ii) PhH, 3 hrs, 80°	H	CH_2COOH	46[ah]	45
105	(i)$BrCH_2COOMe$, (ii) Bu_3SnH	(i)Pentane, hν, 6 hrs, rt, (ii) PhH, 3 hrs, 80°	H	CH_2COOEt	3[c]	10

Table 1. Continued

Entry	Co-Reactants X—Y	Conditions	X	Y	Yield (%)	Ref
106	(i) ICH_2COOEt, (ii) Bu_3SnH, 4-$ClC_6H_4CH{=}CH_2$	(i)Et_2O, hv, 3 hrs, 0°; (ii) PhH, 3 hrs, 80°	CH_2COOH H	4-ClC_6H_4-CH_2CH_2 CH_2COOH	24[ach] 21[ach]	45
107	(i) $I(CH_2)_4Me$, (ii) Bu_3SnH, $CH_2{=}CCl_2$	(i)Et_2O, hv, 3 hrs, 0°; (ii) PhH, 2 hrs, 80°	CH_2CH_2Cl	$(CH_2)_4Me$	36[a]	45
108	(i) $I(CH_2)_4Me$, (ii) Bu_3SnH, $(MeCO)_2$	(i)Et_2O, hv, 3 hrs, 0°; (ii) PhH, 3 hrs, rt	COMe	$(CH_2)_4Me$	43[a]	45
109	(i)  (ii) Bu_3SnH, $CH_2{=}CHCOOMe$	(i)Et_2O, hv, 1 hr, 0°; (ii) PhH, 2 hrs, 80°	CH_2CH_2-COOMe		39[a]	45
110	(i) ICH_2COPh, (ii) Bu_3SnH, $MeCOCF_3$	(i)Et_2O, hv, 1 hr, 0°; (ii) PhH, 1 hr, 80°	C(Me)(OH)-CF_3	CH_2COPh	39[a]	45
111	(i) $I(CH_2)_5Me$, (ii) Bu_3SnH, MeCOCN	(i)Et_2O, hv, 1 hr, 0°; (ii) PhH, 3 hrs, rt	CH(OH)CN	$(CH_2)_4Me$	35[ai]	45
112		PhH, hv	I		nr	6
113		PhH, hv	I		nr	6
114		PhH, hv	I			44,60
115[j]	(i)  (ii) Bu_3SnH, MeCOCOOMe	(i)Et_2O, hv, 1 hr, 0°; (ii) PhH, hv, 3 hrs, rt	C(Me)(OH)-COOMe		49[a]	45

a) Yield based on tetrahalide. b) nr = Yield not reported. c) Higher staffanes also obtained. d) Combined yield. e)R,S and R,R mixture, not separated. f) By analogy with data contained in entries 97-100 this substituent is shown as Cl rather than as $SO_2C_6H_4Me$ as claimed in the original paper. g) BPMDA= *bis*(phenylmethyl)diazene. h) After hydrolysis. i) Isolated as the ketone (see entry 108). j) A = Acetate.

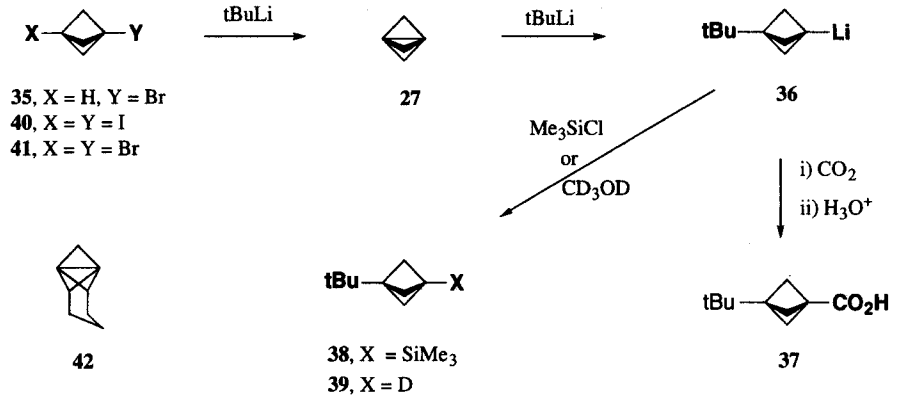
2. Ionic Ring Opening

i. Addition of Organometallic Reagents

Treatment of 1-bromobicyclo[1.1.1]pentane (**35**)[61] with *t*-butyllithium followed by CO_2 was found to give 3-*t*-butylbicyclo[1.1.1]pentane-1-carboxylic acid (**37**) rather than the expected parent acid. This transformation has been ascribed to the production of [1.1.1]propellane (**27**) *in situ*

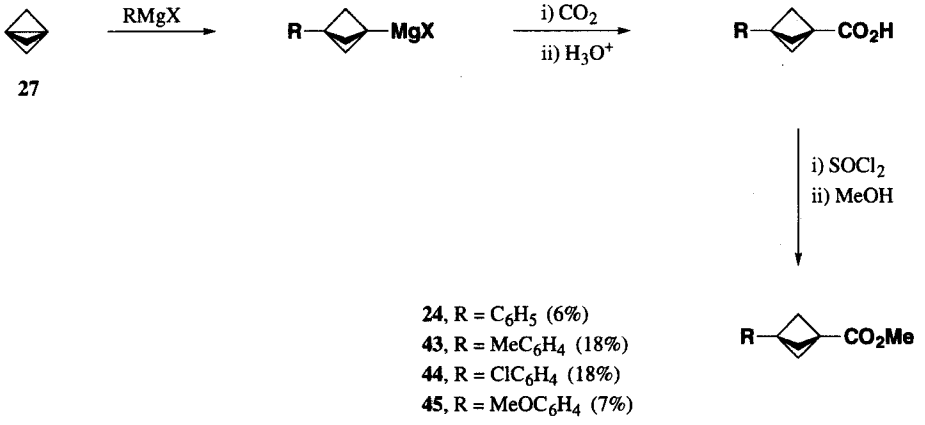
by a 1,3-elimination of the elements of HBr; subsequent reaction of **27** with *t*-butyllithium leads to ring-opening and delivers the bridgehead lithiated species **36** (Scheme 4). Evidence for this mechanism is provided by the observation that exposure of **27** to *t*-BuLi and quenching of the mixture with CO_2 leads to the acid **37**. The silane **38** and hydrocarbon **39** were obtained by working up the reaction with chlorotrimethylsilane[61] and CD_3OD[55] respectively. Similar treatment of 1,3-diiodobicyclo[1.1.1]pentane (**40**), or the 1,3 dibromide **41**, with *t*-butyllithium afforded **37**, via [1.1.1]propellane, in 85% yield[38].

Interestingly, addition of other organolithium reagents such as phenyllithium or methyllithium to [1.1.1]propellane (**27**) has not been reported, although the former has been shown[62] to lead to ring-opening in its reaction with the modified [1.1.1]propellane **42**.



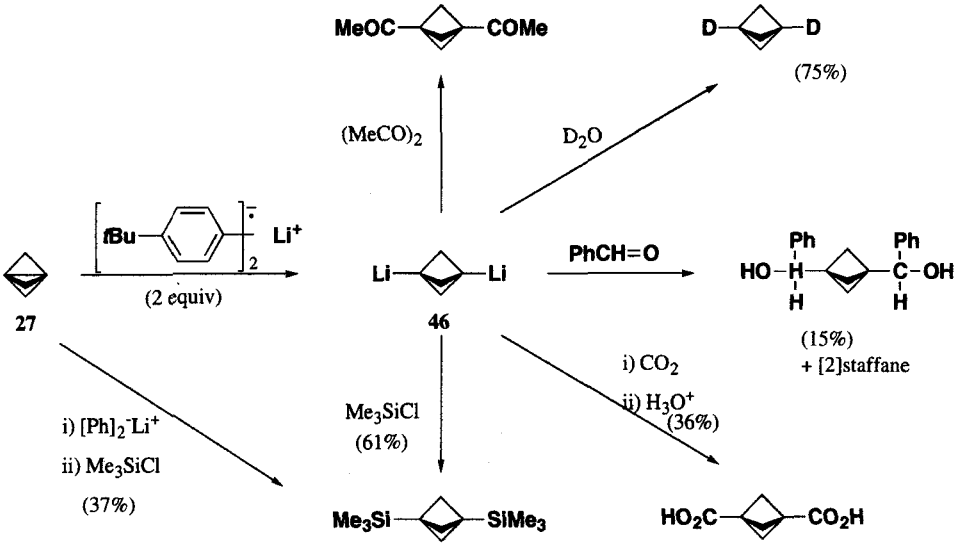
Scheme 4

Addition of Grignard reagents to [1.1.1]propellane appears to be much less facile than its reaction with *t*-butyllithium. Wiberg and McMurdie[47] find that the bicyclo[1.1.1]pentyl ester **24** is obtained by heating [1.1.1]propellane with phenylmagnesium halide in boiling ether for 24 hours followed by the combination of reagents depicted (Scheme 5). The related esters **43-45** were obtained in a similar way.



Scheme 5

Bunz and Szeimies[63] synthesised a number of symmetrically-substituted 1,3-bicyclo[1.1.1]-pentanes from the dilithiated species **46**, generated by treating [1.1.1]propellane with lithium 4-4′-di-*tert*-butylbiphenyl (Scheme 6). Reduction of **27** could also be effected by lithium biphenyl itself, although inferior yields were obtained in these cases.



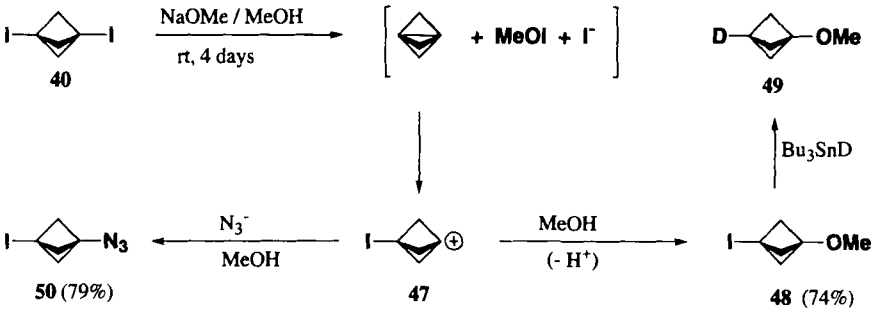
Scheme 6

ii. Addition of Electrophiles

The reaction of electrophiles with [1.1.1]propellane occurs rapidly, generally giving ring-opened products only. This is consistent with the results of calculation which predict that the 1-bicyclo[1.1.1]pentyl cation rearranges to the 3-methylenecyclobutyl cation without a significant activation barrier[64]. Although the 1-bicyclo[1.1.1]pentyl cation itself has so far eluded capture under nucleophilic conditions, its 3-iodo analog is less prone to rearrangement and has been intercepted on several occasions. Thus, Wiberg and McMurdie[65] observed that treatment of the 1,3-diodobicyclo[1.1.1]pentane (**40**) with I_2/NaOH in methanol leads to its conversion, via [1.1.1]propellane, to 3-methoxybicyclo[1.1.1]pentyl iodide (**48**) in good yield. This proved to be a useful synthetic procedure for the preparation of **48**[38,52] and **49**[55] which were required in other studies. The mechanism for the process is depicted in Scheme 7; it involves the 3-iodocation **47** as the key intermediate which, in the presence of the strongly nucleophilic azide ion as trapping agent, afforded the azide **50** as the major product.

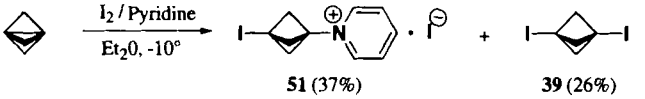
Conversion of the 1,3-diiodide **40** into 3-iodobicyclo[1.1.1]pentyl bromide by treatment with bromine/CCl_4 at 0°[47,65] is accompanied by significant quantity of rearranged products and most likely proceeds via the cation **47** also. Interestingly, in this context, the reaction between [1.1.1]propellane and iodine has also been interpreted[66] in terms of a dual mechanism of addition. Thus, when the addition is conducted in the presence of lithium bromide there appears to be an addi-

tional channel for reaction, besides a pathway mediated by radical intermediates[67], which involves cations. Thus, Szeimies and Belzner[68] and Della and Taylor[69] have independently found that the 3-iodobicyclo[1.1.1]pentyl bromide was formed along with the diodide **40**.

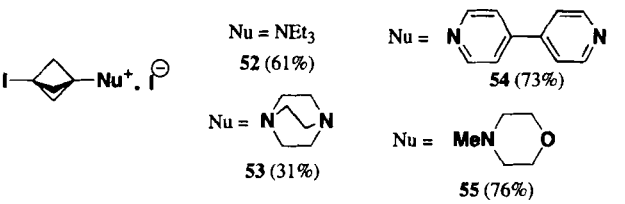


Scheme 7

It has been suggested[52,70] that the cation **47** is the intermediate in the ring-opening reaction of [1.1.1]propellane with iodine and pyridine which gives a mixture of the pyridinium salt **51** (37%) and the diiodide **40** (23%) (Eq. 11). The salts **52-55** were obtained in the yields specified when other amines were used.



(11)



III. SYNTHESIS OF BRIDGEHEAD-SUBSTITUTED BICYCLO[1.1.1]PENTANES BY INTERCONVERSION OF SUBSTITUENTS

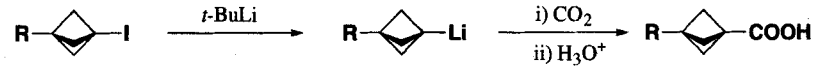
1. Bicyclo[1.1.1]pentane-1-carboxylic Acids

Carboxylic acids are widely used as precursors for the preparation of many other derivatives and, in view of their versatility, it is appropriate that the methods employed for the synthesis of the bridgehead bicyclo[1.1.1]pentanecarboxylic acids are discussed first. Such preparations can be accomplished by a variety of procedures and the preferred route is usually predicated by the availability of the precursor. Methods found to be generally applicable include:

i. Carbonation of Metallated Bicyclo[1.1.1]pentanes

Reference has already been made (Schemes 4 and 5, Section II.2.i above) to the synthesis of 1-bicyclo[1.1.1]pentanecarboxylic acids via metallation of [1.1.1]propellane[38,47,61,63] by *tert*-butyl-

lithium and Grignard reagents. In addition to these, the parent acid **58** itself has been obtained[71] by carbonation of 1-lithiobicyclo[1.1.1]pentane (**57**) derived from 1-iodobicyclo[1.1.1]pentane (**56**) by the metathesis exchange illustrated. A similar route was followed for the synthesis of 3-methylbicyclo[1.1.1]pentane-1-carboxylic acid (**61**) and its ^{13}C-labelled isomer **64** from the corresponding iodides **59** and **62** via the metallated species **60** and **63**[49].



56, R = H — **57**, R = H — **58**, R = H (75% overall)

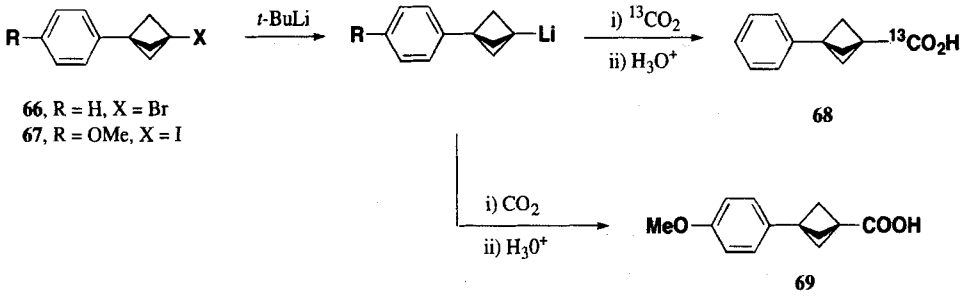
59, R = CH_3 — **60**, R = CH_3 — **61**, R = CH_3 (90% overall)

62, R = $^{13}CH_3$ — **63**, R = $^{13}CH_3$ — **64**, R = $^{13}CH_3$

Alternatively, **57** can be produced by reduction of bicyclo[1.1.1]pentyl phenyl sulfide (**28**) by lithium 4,4'-di-*tert*-butylbiphenyl[42,72]. A major disadvantage of this procedure is the reduced yield of acid as a result of the two possible modes of cleavage of **28** by the reagent giving **57** accompanied by significant quantities of lithium 1-bicyclo[1.1.1]pentylthiolate (**65**).

28 — **65** — **57** — **58** (45% overall)

The ^{13}C-labeled acid **68**[34] and 3(4-methoxyphenyl)-bicyclo[1.1.1]pentanecarboxylic acid (**69**)[38] were synthesised, as depicted, by treatment of the respective arylated bicyclo[1.1.1]pentyl halides (**66** and **67**) with *t*-butyllithium.

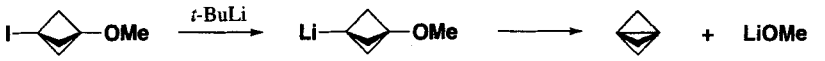


66, R = H, X = Br
67, R = OMe, X = I

68

69

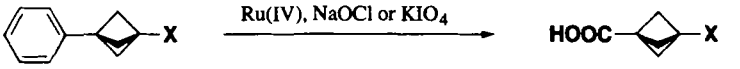
Interestingly, attempts to metallate 3-iodobicyclo[1.1.1]pentyl methyl ether (**48**) failed[38]. This was ascribed to the lability of the intermediate lithio derivative **70** which was suggested to collapse spontaneously giving [1.1.1]propellane (**27**) (Eq. 12).



48 — **70** — **27** (12)

ii. Oxidation of Phenylbicyclo[1.1.1]pentanes

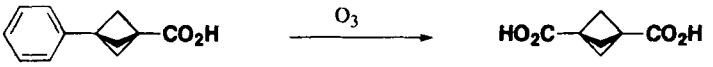
Applequist and his associates[31] were the first to prepare bicyclo[1.1.1]pentanecarboxylic acids by exploiting the demonstration that ruthenium(IV) mediated oxidation of the phenyl substituent provides easy access to the carboxy group[73] and they obtained the acids **71, 73, 34** and **75** in this way. An advantage of this procedure is its cost-effectiveness because only a catalytic quantity of the ruthenium species is required. It was found necessary[31] to exercise caution in the conversion **74** → **75** because the presence of excessive quantities of oxidant (Chlorox) afforded a product contaminated with significant amounts of the alcohol **76**.



23, X = CN
72, X = NO_2
24, X = COOMe
74, X = OCOMe
77, X = $^{13}CO_2Me$
79, X = $SiMe_3$
81, X = $SnMe_3$

71, X = CN (56%)
73, X = NO_2 (44%)
34, X = CO_2Me (62%)
75, X = OCOMe (52%) + **76**, X = OH
78, X = $^{13}CO_2Me$ (83%)
80, X = $SiMe_3$ (74%)
82, X = Cl

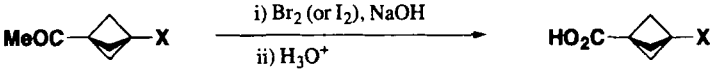
Della and associates[34] observed that the synthesis of the ^{13}C-labeled derivative **78** could be achieved in excellent yield by oxidation of **77** and, more recently, it was observed by the same group[38] that preparation of the silane **80** could be accomplished in good yield by this procedure. However, attempted oxidation of the corresponding stannane **81** met with failure[38]; under the oxidative conditions only the 3-chloro acid **82** was detected in the product. Wiberg and coworkers[32] report that oxidation of **83** to the diacid **32** could be effected in good yield (62%) by ozonolysis.



83 **32**

iii. Oxidation of Acetylbicyclo[1.1.1]pentanes

As discussed earlier, Kaszynski and Michl[57] developed a very attractive route to bicyclo[1.1.1]pentane-1,3-dicarboxylic acid **32** via the diacetyl derivative **31** produced by addition of biacetyl to [1.1.1]propellane. Oxidation of **31** was achieved readily and in high yield by treatment with hypobromite. The related ketones **84** and **85** afforded the acids **83**[10] and **86**[10,14], respectively, in excellent yields under similar conditions.

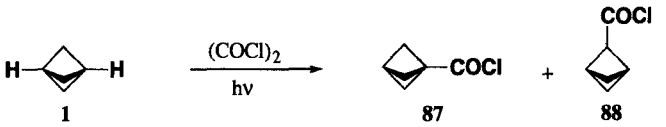


31, X = COMe
84, X = Ph
85, X = Bu

32, X = CO_2H
83, X = Ph
86, X = Bu

iv. Photochemical Haloacylation of Bicyclo[1.1.1]pentane

Wiberg and Williams[1] observed that UV irradiation of a solution of bicyclo[1.1.1]pentane (**1**) and oxalyl chloride in Freon 11 produced an 85:15 mixture (73% yield) of the isomeric 1- and 2-bicyclo[1.1.1]pentanecarboxylic acid chlorides (**87** and **88**) (Eq. 13). These were not separated, but were converted into the corresponding esters from which the bridgehead-substituted isomer could be isolated by preparative gas chromatography.



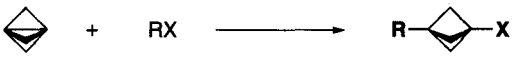
1 **87** **88** (13)

2. 1-Halobicyclo[1.1.1]pentanes

Incorporation of halogen at the bridgehead of bicyclo[1.1.1]pentane has undoubtedly received the most intensive synthetic effort among its many known derivatives and a number of procedures leading to halobicyclo[1.1.1]pentanes are therefore available.

i. Addition of Haloalkanes to [1.1.1]Propellane.

The addition reactions between [1.1.1]propellane and various haloalkanes (Eq. 14) referred to in Table 1 (entries 11-14, 21-34, 36-47, 97-101 and 112-114) represent an important synthetic pathway to 1-halobicyclo[1.1.1]pentanes.



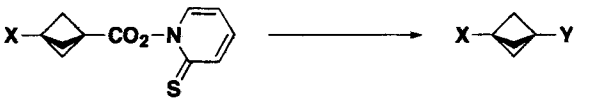
(14)

ii. From Bicyclo[1.1.1]pentane-1-Carboxylic Acids

The conversion of bridgehead carboxylic acids into halides via the Barton ester has been exploiteded largely by Della and his associates, and this procedure has become the method of choice for the synthesis of bicyclo[1.1.1]pentyl bridgehead halides over more recent years largely as a result of the ease of preparation of the corresponding carboxylic acids. The conversions recorded to date are assembled in Table 2. Inspection of the Table reveals that in some instances the preformed Barton ester is employed while in others the ester is formed *in situ* (entries 2, 6, 24, 27-30), and, while both procedures work particularly well, the former generally does better. Although the presence of a number of other substituents can be tolerated, there are several situations when the procedure fails (entries 31-35); this has been attributed to the lability of the intermediate radical which collapses to give [1.1.1]propellane as a result of the ease of extrusion of the substituent X (I[69], SePh, $SnMe_3$ and $SiMe_3$[38]).

A closely related transformation involving bromodecarboxylation under Hunsdiecker conditions was successfully employed some years ago for the conversion of the half ester **34** into **89** (68%)[31], and the diacid **32** into the dibromide **41** (68%)[32]. However, the advent of the Barton ester synthesis of bridgehead halides has essentially relegated the formerly popular Hunsdiecker halodecarboxylation procedure, including its modifications, to one of historical interest.

Table 2. Synthesis of Bridgehead-Substituted Bicyclo[1.1.1]pentanes by Halodecarboxylation

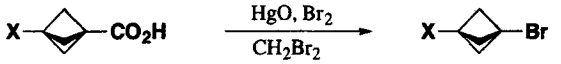


Entry	Conditions	X	Y	Yield (%)	Ref
1	$CFCl_3$, hν, 1.5 hrs, rt	H	Cl	87	71
2	CF_3CCl_3, hν, 2 hrs, 50°[a]	H	Cl	47	74
3	$CF_3CHBrCl$, hν, 1 hr, rt	H	Br	68	75
4	$CF_3CHBrCl$, hν, 1 hr, rt	D	Br	60	76
5	CF_3CH_2I/CH_2Cl_2, hν, 30min, rt	H	I	87	71
6	CF_3CH_2I, hν, 1 hr, 57°[a]	H	I	62	47
7	$CF_3CHBrCl$, hν, 1 hr, rt	Cl	Br	80	38
8	CF_3CH_2I/C_6H_5, hν, 1 hr, rt	Cl	I	89	69
9	CF_3CCl_3, hν, 2 hrs, rt	Br	Br[b]	45	38
10	CF_3CH_2I, hν, 1 hr, rt	Br	I	45	38
		Br	Br	10	
11	$CFCl_3/CH_2Cl_2$, hν, 2 hrs, rt	Me	Cl	17	48
12	$CFCl_3/CH_2Cl_2$, hν, 2 hrs, rt	^{13}Me	Cl	nr	49
13	$CF_3CHBrCl$, hν, 1 hr, rt	Me	Br	81	38
14	$CF_3CHBrCl$, hν, 1 hr, rt	^{13}Me	Br	25	48
15	$CF_3CHBrCl$, hν, 1 hr, rt	CN	Br	83	38
16	$CF_3CHBrCl$, hν, 1 hr, rt	COMe	Br	94	38
17	$CFCl_3$, hν, 1 hr, rt	COOMe	Cl	82	38
18	$CF_3CHBrCl$, hν, 1 hr, rt	COOMe	Br	95	38
19	CF_3CH_2I/C_6H_5, hν, 1 hr, 50°	COOMe	I	81	77
20[c]	$CF_3CHBrCl$, hν, 40min, 47°	F	Br	83	78
21	$CF_3CHBrCl$, hν, 1 hr, rt	*t*-Bu	Br	89	38
22	$CF_3CHBrCl$, hν, 1 hr, rt	Ph	Br	89	38
23	$CF_3CHBrCl$, hν, 1 hr, 47°[a]	Ph	Br	88	34
24	CF_3CH_2I, hν, 1 hr, 50°[a]	Ph	I	92	47
25	$CF_3CHBrCl$, hν, 1 hr, rt	4-$MeOC_6H_4$	Br	81	38
26	$CF_3CHBrCl$, hν, 1 hr, rt	4-$O_2NC_6H_4$	Br	85	38
27	CF_3CH_2I, hν, 1 hr, 50°[a]	4-ClC_6H_4	I	96	47
28	CF_3CH_2I, hν, 1 hr, 50°[a]	4-MeC_6H_4	I	96	47
29	CF_3CH_2I, hν, 1 hr, 50°[a]	4-$MeOC_6H_4$	I	87	47
30	CF_3CH_2I, hν, 1 hr, 50°[a]	4-$O_2NC_6H_4$	I	96	47
31	$CF_3CHBrCl$, hν, 1 hr, rt	I	Br	0	69
32	CF_3CH_2I, hν, 1 hr, rt	I	I	0	69

Table 2. Continued

Entry	Conditions	X	Y	Yield (%)	Ref
33	$CF_3CHBrCl$, hv, 1 hr, rt	C_6H_5Se	Br	0	38
34	$CF_3CHBrCl$, hv, 1 hr, rt	Me_3Si	Br	0	38
35	$CF_3CHBrCl$, hv, 1 hr, rt	Me_3Sn	Br	0	38

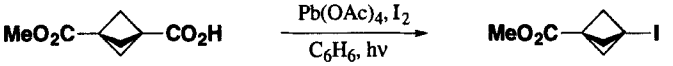
a) Reaction performed on the acid chloride/  in the presence of a catalytic amount of dimethylaminopyridine. b) [1.1.1]Propellane also produced; the expected 3-chlorobicyclo [1.1.1]pentyl bromide was not detected in the product. c) A 7:3 mixture of the 3-fluoroacid and bicyclo[1.1.1]pentanecarboxylic acid used.



34, X = CO_2Me
32, X = CO_2H

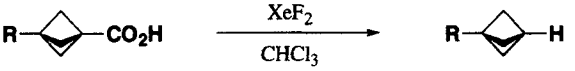
89, X = CO_2Me
41, X = Br

Decarboxylative iodination can be performed very conveniently by treatment of the acid with a mixture of $Pb(OAc)_4$ and iodine in boiling benzene under irradiation. This method possesses several advantages including its ease of operation, the fact that it is a one-step operation, and that it proceeds in excellent yield. For example, 3-carbomethoxybicyclo[1.1.1]pentyl iodide (**90**) was obtained in 91% yield under these conditions (Eq. 15)[77].



34 **90** (15)

Although fluorodecarboxylation can be accomplished by treatment of a carboxylic acid with xenon difluoride[79] and has, indeed, been shown to be an effective method for the preparation of bridgehead fluorides in general[77], it fails in the case of bicyclo[1.1.1]pentane carboxylic acids. Thus, in the case of the bicyclo[1.1.1]pentanecarboxylic acids **83**[45] and **34**[77] only the reduced products **91** and **92** were observed (Eq. 16).



83, R = C_6H_5
34, R = COOMe

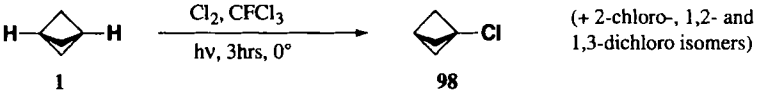
91, R = C_6H_5
92, R = COOMe (16)

Aside from the preparation of the parent (**13**)[26] referred to earlier, the synthesis of 3-substituted-1-fluorobicyclo[1.1.1]pentanes had not been reported until very recently, a feature which reflects the difficulty of inserting fluorine at the bridgehead position. Thus, Adcock and Walton and their associates[78] find that treatment of the metallated derivative **93**, produced by the metathesis reaction of the protected bromobicyclo[1.1.1]pentyl acid **92** and *tert*-butyllithium, with N-fluorosultam followed by

hydrolysis to remove the protecting group yields a 7:3 mixture of the fluoride **94** and the reduced product **95**. Hydrolysis of the product gave an inseparable 7:3 mixture of 3-fluorobicyclo[1.1.1]-pentanecarboxylic acid (**96**) and bicyclo[1.1.1]pentanecarboxylic acid (**58**) which, as outlined in Table 2, undergo bromodecarboxylation via the Barton esters to give the corresponding mixture of bromides **97** and **35**. Adcock and Krstic[80] have presented NMR measurements on a series of 3-substituted bicyclo[1.1.1]pentyl fluorides and foreshadowed the description of the syntheses of these fluorides in the full paper.

iii. via Radical-Chlorination of Bicyclo[1.1.1]pentane

Wiberg and his coworkers[1] were the first to record a successful synthesis of a bicyclo[1.1.1]pentane substituted with halogen at the bridgehead by treatment of the parent, bicyclo[1.1.1]pentane, with t-butyl hypochlorite under photochemical irradiation. This yielded a mixture of the chloride **98** (7%) and other chlorinated bicyclo[1.1.1]pentanes. They subsequently reported[81,82] an improved chlorination procedure which afforded **98** in over 30% yield. However, in view of the need for preparative GC to separate the monochloride from the other chlorinated bicyclo[1.1.1]pentane byproducts, this method has been superseded by the more recent developments described above leading to facile syntheses of these derivatives from Barton ester precursors.



1 **98**

3. Miscellaneous Bridgehead Derivatives

i. Carboxylic Acids as Precursors

a. *via* Barton Esters

The ease of preparation and smooth decomposition of Barton esters, induced either thermally or photochemically, has not only been employed for the synthesis of the corresponding halides (Section III.2.ii), but also for the preparation of a variety of bridgehead-substituted bicyclo[1.1.1]pentanes. Indeed, this methodology presents a relatively simple entry to a number of derivatives which are otherwise either inaccessible or prepared with great difficulty. Table 3 depicts the range of compounds which have been synthesised this way. Scrutiny of the Table reveals that while the yields are generally very good to excellent, there are several exceptions.

b. via Peroxyesters

Although thermal-induced decomposition of *tert*-butyl peroxyesters proceeds smoothly giving bicyclo[1.1.1]pentyl radicals, this process has only been used on rare occasions as a route to functionalised bicyclo[1.1.1]pentanes and, as Michl and coworkers[45] have shown (Table 3, entries 19-23), it is not an especially viable synthetic procedure.

Table 3. Conversion of Bicyclo[1.1.1]pentanecarboxylic Acids into Derivatives other than Halides *via* their Barton and *t*-Butyl Peroxy Esters

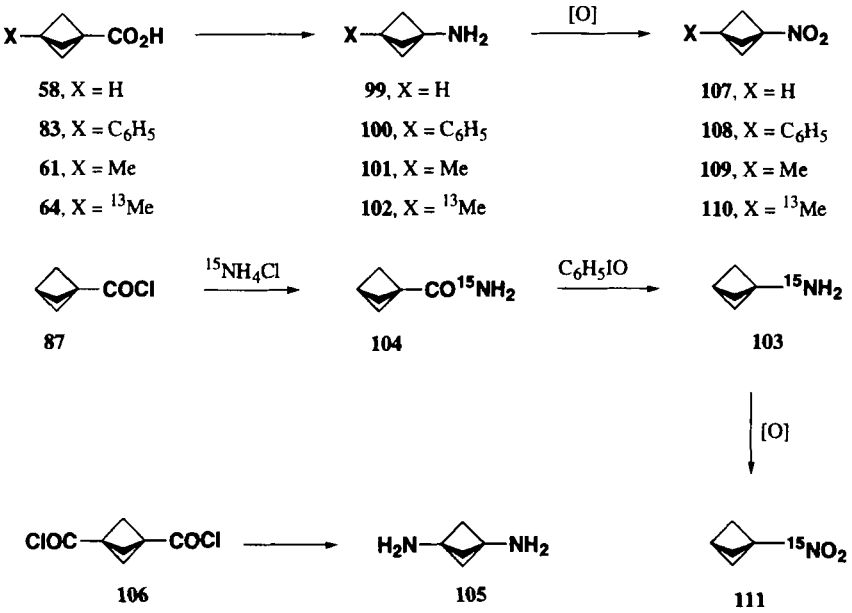
Entry	Conditions	X	Y	Yield (%)	Ref
1[a]	Bu_3SnH, hv, 30min	H	H	73	71
2[a]	*t*-BuSH/C_6H_5, hv, 80°[b]	COOMe	H	74[c,d]	83
3[a]	*t*-BuSH/C_6H_5, hv, 80°[b]	^{13}COOMe	H	74[c,d]	34
4[a]	$(PhS)_2$, C_6H_5, hv, rt, 2 hrs	Me	SPh	32	49
5[a]	$(PhS)_2$, C_6H_5, hv, rt, 2 hrs	^{13}Me	SPh	nr	49
6[a]	$(PhSe)_2$, C_6H_5, hv, rt, 25min	H	SePh	74	71
7[a]	$(PhSe)_2$, CH_2Cl_2, hv, rt, 40min	Me	SePh	71	49
8[a]	$(PhSe)_2$, CH_2Cl_2, hv, rt, 40min	^{13}Me	SePh	nr	49
9[a]	$(PhSe)_2$, CH_2Cl_2, hv, rt, 20min	COOMe	SePh	77	38
10[a]	$(Me_3Sn)_2$, C_6H_5, hv, rt, 30min	COOMe	Me_3Sn	40	38
11[a]	$(Me_3Si)_2$, C_6H_5, hv, rt, 30min	COOMe	Me_3Si	0	38
12[a]	XeF^2, CH_2Cl_2, rt, 1min	COOMe	COF	95	38
13[a]	$(MeCO)_2$, CH_2Cl_2, hv, rt, 30min	COOMe	COMe	84	38
14[a]	$(MeCO)_2$, C_6H_5, hv, 1.5 hrs, 30°[b]	COOMe	COMe	70	45
15[a]	$(MeCOS)_2$, C_6H_5, hv, 1.5 hrs, 30°[b]	COOMe	SCOMe	85[c,e]	45
16[a]	$P(OEt)_3$, C_6H_5, hv, 1.5 hrs, 30°[b]	COOMe	$PO(OEt)_2$	28[c]	45
17[a]	C_6H_5, hv, 1.5 hrs, 80°[b]	COOMe	C_6H_5	10[c]	45
		COOMe	SC_6H_4N[f]	70[c]	
18[a]	Acridine, C_6H_5, hv, 1.5 hrs,	COOMe	5-Acridino	20[c]	45
19[g]	3 hrs, 130°	H	COOMe	26	45
		COOMe	*t*-BuO	8	
20[g]	C_6H_5Cl, 4 hrs, 130°	COOMe	$-C_6H_4Cl$	nr[h]	45
21[g]	C_6H_5CN, 4 hrs, 130°	COOMe	$-C_6H_4CN$	nr[h]	45
22[g]	C_6H_5COOMe, 4 hrs, 130°	COOMe	$-C_6H_4COOMe$	nr[h]	45
23[g]	1,4-Dichlorobenzene, 4 hrs, 130°	COOMe	$2,5\text{-}Cl_2C_6H_3$	13	45
		COOMe	*t*-BuO	7	

a) R =  b) See note in Table 2. c) Yields based on carboxylic acid. d) Isolated as the carboxylic acid. e) After workup with Zn/HOAc. f) 2-Pydridylthio. g) R = OBu^t. h) Mixture of *o*-, *m*-, and *p*-isomers.

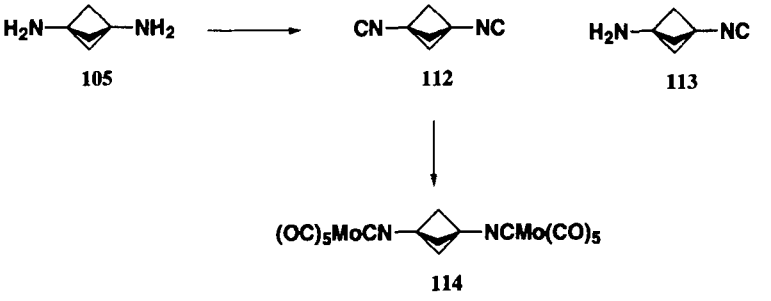
c. From Carboxy Group to Nitrogen

Wiberg and his colleagues[82] reported that transformation of 1-bicyclo[1.1.1]pentanecarboxylic acid (**58**) into 1-aminobicyclo[1.1.1pentane (**99**) could be effected under Schmidt conditions. 3-Phenylbicyclo[1.1.1]pentylamine (**100**)[31], 3-methylbicyclo[1.1.1]pentylamine (**101**)[49] and its ^{13}C-

labelled isomer **102**[49] were prepared from the corresponding acids **61** and **64** in a similar way. For the synthesis of the ^{15}N-labelled isomer **103**, Della et al.[35] found it convenient to introduce the label by generating the amide **104** from reaction of the acid chloride **87** with $^{15}NH_4Cl$ after which the amide was induced to undergo a Hofmann rearrangement by treatment with iodosobenzene. Preparation of the diamine **105** (yield 77%) was performed by Michl and coworkers[84] using a classical Curtius sequence on the diacid chloride **106**. Oxidation of the amines **99**[55], **100**[31], **101**[49], **102**[49] and **103**[85] by *m*-chloroperbenzoic acid gave good yields of the corresponding nitro derivatives **107-111**.



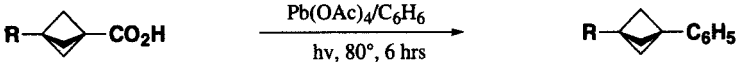
The diamine **105** was found to react with dichlorocarbene under phase transfer conditions to give a 2:1 mixture (61% yield) of the diisonitrile **112** and aminoisonitrile **113**[84]. Upon irradiation in the presence of molybdenum hexacarbonyl, the former yielded the bis-pentacarbonyl molybdenum complex **114**.



d. From Carboxy Group to Phenyl

Application of the decarboxylative arylation technique described by Moriarty and colleagues[86] to the carboxylic acid **34** gave methyl 3-phenylbicyclo[1.1.1]pentanecarboxylate (**24**)[38] in

good yield. This represents a vast improvement on the procedure for the preparation of **24** referred to above (Scheme 1 and Eq. 6). It is noteworthy that in order to obtain optimum yields it is essential at the outset that the reaction mixture be thoroughly deoxygenated. The hydrocarbon **115** was synthesised from 3-methylbicyclo[1.1.1]pentanecarboxylic acid (**61**) in a similar manner[49].

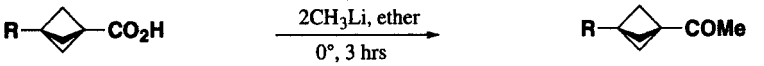


34, R = COOMe
61, R = Me

24, R = COOMe
115, R = Me

e. From Carboxy Group to Ketones to Esters

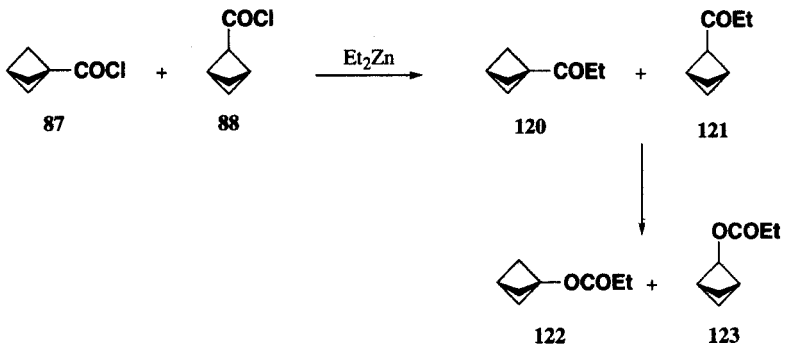
Standard methodology for the conversion of the acid group into ketones by treatment with 2 equivalents of alkyllithium has been applied successfully for the synthesis of the methyl ketones **116** and **84**, respectively, in very good yield from 3-methyl- (**61**) and 3-phenylbicyclo[1.1.1]pentanecarboxylic acid (**83**)[31]. Essentially identical conditions were employed for the preparation of the isotopomers **118** and **119** in good yield from the corresponding acids **58** and **117**[55].



61, R = Me
83, R = C_6H_5
58, R = H
117, R = D

116, R = Me
84, R = C_6H_5
118, R = H
119, R = D

The mixture of 1- and 2-chlorocarbonylbicyclo[1.1.1]pentanes (**87** and **88**) described earlier (Eq. 13) could be converted into the mixture of ethyl ketones **120** and **121** (55%) by exposure to diethylzinc[82].



87 **88** **120** **121** **122** **123**

Oxidation of the acetyl groups so produced was effected successfully under Baeyer-Villiger conditions. Thus, the mixture of ketones **120** and **121** gave the esters **122** and **123** when treated with *m*-chloroperbenzoic acid[82]. Under similar conditions, 3-bromobicyclo[1.1.1]pentyl methyl ketone (**124**)[38] and the related ketones **84**[31], **118**[55] and **116**[49] afforded the corresponding acetates **125-128**, respectively, in high yield. Wiberg and Waddell[42] determined the relative migratory aptitude of the [1.1.1]bicyclopentyl ring and the *t*-butyl group by analysing the product distribution from Baeyer-Villiger oxidation of bicyclo[1.1.1]pentyl *t*-butyl ketone (**129**). A 2.3:1 mixture of *t*-butyl bicyclo[1.1.1]pentanecarboxylate (**130**) and bicyclo[1.1.1]pentyl pivalate (**131**) was observed.

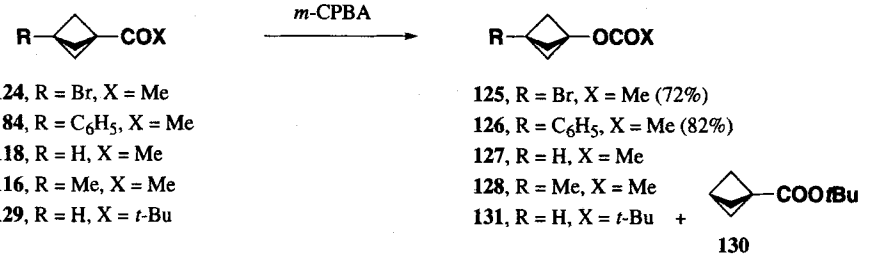


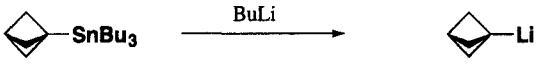
Table 4. Conversion of Bridgehead Metallated Bicyclo[1.1.1]pentanes into Derivatives Other than Carboxylic Acids and Halides

	Reactant		Reagents		Product			
Entry	X	Y	R	R'	X	Z	Yield (%)	ref
1	H	I	*t*-BuLi	$(C_6H_5Se)_2$	H	C_6H_5Se	76	71
2	C_6H_5	I	*t*-BuLi	Me_3SnCl	C_6H_5	Me_3Sn	8	38
3	C_6H_5	I	*t*-Bu Li	Me_3SiCl	C_6H_5	Me_3Si	92	38
4	H	Me_3Sn	BuLi	LiNHOMe	H	NH_2[a]	24	38
5	H	Me_3Sn	BuLi	$(C_6H_5S)_2$	H	C_6H_5S	40	54
6	CF_3	I	C_6H_5Li		CF_3	C_6H_5	40	52
7	CF_3	I	MeLi		CF_3	Me	50	52
8	H	SC_6H_5	LDTBB[b]	$C_8H_{17}I$/CuI	H	C_8H_{17}	25	42
9	H	SC_6H_5	LDTBB[b]	Bu_3SnCl	H	Bu_3Sn	50	42
10	H	SC_6H_5	LDTBB[b]		H		22	42
					H		25	
11	H	SC_6H_5	LDTBB[b]	(i) O_2, (ii) C_6H_5COCl	H H	$OCOC_6H_5$ $SCOC_6H_5$	17 17	42
12	H	SC_6H_5	LDTBB[b]	*t*-BuCHO	H	CH(OH)-*t*-Bu	60	42
13	H	SC_6H_5	LDTBB[b]	C_6H_5CHO	H	$CH(OH)-C_6H_5$	57	42
14	H	SC_6H_5	LDTBB[b]	HCOOMe	H	CHO	21	42
15	H	SC_6H_5	LDTBB[b]	*t*-$(BuO)_2$	H	OBu^t	15	42
16	H	SC_6H_5	LDTBB[b]	*t*-BuCN	H	$COBu^t$	60	42
17	H	SC_6H_5	LDTBB[b]	Me_3SiCl	H	Me_3Si	12	42
18	H	SC_6H_5	LDTBB[b]	MeOD	H	D	27	42,72
19	H	SC_6H_5	LDTBB[b]	C_6H_5CN	H	COC_6H_5	50	42

a) Isolated as the benzoate. b) Lithium di-*tert*-butylbiphenyl.

ii. From Bridgehead Metallated Bicyclo[1.1.1]pentanes

Whereas exposure of 1-bromobicyclo[1.1.1]pentane (**35**) to *tert*-butyllithium leads to elimination of HBr (Section 3.1.1), treatment of 1-iodobicyclo[1.1.1]pentane[71] (**56**) with *tert*-butyllithium results in the expected metathesis reaction and yields 1-bicyclo[1.1.1]pentyllithium (**57**). 1-Tributyltinbicyclo[1.1.1]pentane[54] (**132**) participates in a similar way, reacting smoothly with butyllithium to give **57** (Eq. 17). These, and other metallated bicyclo[1.1.1]pentanes, have been employed for the synthesis of a wide range of bridgehead-substituted bicyclo[1.1.1]pentanes as depicted in Table 4.



132 57 (17)

REFERENCES

1. a) K. B. Wiberg, D. S. Connor and G. M. Lampmann, *Tetrahedron Letters*, 531 (**1964**); b) K. B. Wiberg and D. S. Connor, *J. Am. Chem. Soc.*, **88**, 4437 (1966).

2. J. L. Adcock, A. A. Gakh, J. L.Pollette and C. Woods, *J. Am. Chem. Soc.*, **114**, 3980 (1992).

3. K. Semmler, G. Szeimies and J. Belzner, *ibid.*, **107**, 6410 (1985).

4. U. Bunz, K. Polborn, H.-U. Wagner and G. Szeimies, *Chem. Ber.*, **121**, 1785 (1988).

5. K. B.Wiberg, *Chem. Rev.*, **89**, 975 (1989).

6. K. Hassenrück, G. S. Murthy, V. M. Lynch and J. Michl, *J. Org. Chem.*, **55**, 1013 (1990).

7. R. Gleiter, G.Szeimies and U. Bunz, *Angew. Chem. Int. Ed. Engl.*, **29**, 413 (1990).

8. H. Bothe and A.-D. Schlüter, *Adv. Mater.*, **3**, 440 (1991).

9. A.-D. Schlüter, H Bothe and J.-M. Gosau, *Makromol. Chem.*, **192**, 2497 (1991).

10. P. Kaszynski, A. C. Friedli and J. Michl, *J. Am. Chem. Soc.*, **114**, 601 (1992).

11. a) P. Kaszynski and J. Michl, *ibid.*, **110**, 5225 (1988); b) For a review of the chemistry of [n]staffanes see P. Kaszynski and J. Michl, "[n]staffanes", in *Advances in Strain In Organic Chemistry*, JAI Press Inc., vol. 4, 283 (1995).

12. A. C. Friedli, P. Kaszynski and J. Michl, *Tetrahedron Lett.*, **30**, 455 (1989).

13. O. Schafer, M. Allan, G. Szeimies and M. Sanktjohanser, *Chem. Phys. Lett.*, **195**, 293 (1992).

14. Friberg, S. E.; Kayali, I.; Kaszynski, P.; Michl, J. *Langmuir*, **8**, 996 (1992).

15. H. C. Yang, T. F. Magnera, C. Lee, A. J. Bard and J. Michl, *iibid.*, **8**, 2740 (1992).

16. Y. S. Obeng, M. E. Laing, A. C. Friedli, H. C. Yang, D. Wang, E. W. Thulstrup, A. J. Bard and J. Michl, *J. Am. Chem. Soc.*, **114**, 9943 (1992).

17. P. Kaszynski, A. C. Friedli and J. Michl, *Mol. Cryst. Liq. Cryst.*, **191**, 193 (1990).

18. P. Kaszynski, A. C. Friedli and J. Michl, *Mol. Cryst. Liq. Cryst. Lett.*, **6**, 27 (1990).

19. C. Ramireddy, V. S. Reddy, P. Munk and C. N. Wu, *Macromolecules*, **24**, 1387 (1991).

20. M. R. Barbachyn, D. K. Hutchinson, D. S. Toops, R. J. Reid, G. E. Zurenko, B. H. Yagi, R. D. Schaadt and J. W. Allison, *Bioorg. Med. Chem. Lett.*, **3**, 671 (1993).

21. M. R. Rifi, *J. Am. Chem. Soc.*, **89**, 4442 (1967); b) M. R. Rifi, *Tetrahedron Letters*, 1043 (**1969**).

22. R. Srinivasan and H. C. Carlough *J. Am. Chem. Soc.*, **89**, 4932 (1967).

23. J. Meinwald, W. Szkrybalo and D. R. Dimmel, *Tetrahedron Letters*, 731 (**1967**).

24. J. Meinwald and R. A. Chapman, *J. Am. Chem. Soc.*, **90**, 3218 (1968).

25. R. Srinivasan, *ibid.*, **90**, 2752 (1968).

26. E. W. Della, E. Cotsaris and P. T. Hine, *ibid.*, **103**, 4131 (1981).

27. E. W. Della and P. E. Pigou, *ibid.*, **106**, 1085 (1984).

28. K. B. Wiberg, G. M. Lampmann, R. P. Ciula, D. S. Connor, P. Schertler, P. and J. Lavanish, *Tetrahedron* , **21**, 2749 (1965).

29. H. K. Hall, C. D. Smith, E. P. Blanchard, S. C. Cherkofsky and J. B. Sieja, *J. Am. Chem. Soc.*, **93**, 121 (1971).

30. D. E. Applequist and J. W. Wheeler, *Tetrahedron Letters*, 3411 (**1977**).

31. D. E. Applequist, T. C. Renken and J. W. Wheeler, *J. Org. Chem.*, **47**, 4985 (1982).

32. K. B. Wiberg, W. P. Dailey, F. H. Walker, S. T. Waddell, L. S. Crocker and M. Newton, *J. Am. Chem. Soc.*, **107**, 7247 (1985).

33. K. B. Wiberg and F. H. Walker, *J. Am. Chem. Soc.*, **104**, 5239 (1982).

34. E. W. Della, H. Gangodawila and P. E. Pigou, *J. Org. Chem.*, **53**, 592 (1988).

35. E. W. Della, B. Kasum, K. P. Kirkbride, *J. Am. Chem. Soc.*, **109**, 2746 (1987).

36. J. Belzner, U. Bunz, K. Semmler, G. Szeimies, K. Opitz and A.-D. Schlüter, *Chem. Ber.*, **122**, 397 (1989).

37. F. Alber and G. Szeimies, *Chem. Ber.*, **125**, 757 (1992).

38. E. W. Della and D. K. Taylor, *J. Org. Chem.*, **59**, 2986 (1994).

39. K. M. Lynch and W. P. Dailey, *J. Org. Chem.*, **60**, 4666 (1995).

40. E. W. Della, P. E. Pigou, C. H. Schiesser, and D. K. Taylor, *J. Org. Chem.*, **56**, 4659 (1991).

41. K. B. Wiberg, S. T. Waddell and K. Laidig, *Tetrahedron Letters*, **27**, 1553 (1986).

42. K. B. Wiberg and S. T. Waddell, *J. Am. Chem. Soc.*, **112**, 2194 (1990).

43. A. V. Blokhin, M. A. Tyurekhodzhaeva, N. K. Sadovaya, and N. S. Zefirov, Izv. Akad. Nauk. SSSR, Ser. Khim. 1993 (1989) (Chem. Abstr., **112**, 178138 (1989).

44. N. S. Zefirov, L. S. Surmina, N. K. Sadovaya, A. V. Blokhin, M. A. Tyurekhodzhaeva, Y. N. Bubnov, L. I. Lavrinovich, A. V. Ignatenko, Yu. K. Grishin, et al., *Zh. Org. Chim.*, **26**, 2317 (1990).

45. P. Kaszynski, N. D. McMurdie and J. Michl, *J. Org. Chem.*, **56**, 307 (1991).

46. R. Gleiter, K. H. Pfeifer, G. Szeimies and U. Bunz, *Angew. Chem.*, **102**, 418 (1990). (*Angew. Chem.Int. Ed. Engl.*, **29**, 413 (1990)).

47. K. B. Wiberg and N. McMurdie, *J. Am. Chem. Soc.*, **116**, 11990 (1994).

48. U. Bunz and G. Szeimies, *Tetrahedron Letters*, **30**, 2087 (1989).

49. I. J. Lochert, PhD Thesis, Flinders University (1996).

50. U. Bunz W. Herpich, J. Podlech, K. Polborn, A. Protzel, D. S. Stephenson and G. Szeimies, *J. Am. Chem. Soc.*, **116**, 7637 (1994).

51. N. S. Zefirov, N. K. Sadovaya, L. S. Surmina, I. A. Godunov, A. S. Koz'min, K. A. Potekhin, A. V. Maleev and Y. T. Struchkov, Izv. Akad. Nauk. SSSR, Ser. Khim. 2648 (1988) (Chem. Abstr., **110**, 212189 1989).

52. J. L. Adcock and A. A. Gakh, *J. Org. Chem.*, **57**, 6206 (1992).

53. M. A. Tyurekhodzhaeva, A. A. Bratkova, A. V. Blokhin, V. K. Brel, A. S. Koz'min and N. S. Zefirov, *J. Fluorine Chem.*, **55**, 237 (1991).

54. D. S. Toops and M. R. Barbachyn, *J. Org. Chem.*, **58**, 6505 (1993).

55. E. W. Della, I. J. Lochert, N. M. Peruchena, G. A. Aucar and R. H. Contreras, *J. Phys. Org. Chem.*, **9**, 168 (1996).

56. K. B. Wiberg, B. S. Ross, J. J. Isbell and N. McMurdie, *J. Org Chem.*, **58**, 1372 (1993).

57. P. Kaszynski and J. Michl, *ibid.*, **53**, 4593 (1988).

58. N. K. Sadovaya, A. V. Blokhin, L. S. Surmina, M. A. Tyurekhodzhaeva, A. S. Koz'min and N. S. Zefirov, *Izv. Akad. Nauk. SSSR, Ser. Khim.*, 2451 (**1990**) (*Chem. Abstr.*, **114** 101181 1991).

59. K. P. Dockery and W. G. Bentrude, *J. Am. Chem. Soc.*, **116**, 10332 (1994).

60. N. K. Sadovaya, A. V. Blokhin, M. A. Tyurekhodzhaeva, M. A. Grishin, L. S. Surmina, A. S. Koz'min and N. S. Zefirov, *Izv. Akad. Nauk. SSSR, Ser. Khim.*, 716 (**1990**) (*Chem. Abstr.*, **113**, 114681 1990).

61. E. W. Della, D. K. Taylor and J. Tsanaktsidis, *Tetrahedron Lett.*, **31**, 5219 (1990).

62. A. D. Schlüter, G. Wegner and W. J. Feast, *Angew. Chem.*, **100**, 283 (1988).

63. U. Bunz and G. Szeimies, *Tetrahedron Lett.*, **31**, 651 (1990).

64. E. W. Della and C. H. Schiesser, *J. Chem. Res. Suppl.*, 172 (**1989**). K. B. Wiberg, C. M. Hadad, S. Sieber and P. R. Schleyer, *J. Am. Chem. Soc.*, **114**, 5820 (1992).

65. K. B. Wiberg and N. McMurdie, *ibid.*, **113**, 8995 (1991).

66. M. Christl, *"Electrophilic Additions to Bicyclo[1.1.0]butanes"*, in *Advances in Strain in Organic Chemistry,* JAI Press Inc., Vol 4, 199 (1995).

67. V. A. Vasin, I. Yu. Bolusheva, E. P. Sanaeva, S. Surmina, N. K. Sadovaya, N. K. Koz'min and N. S. Zefirov, *Dokl. Akad. Nauk. SSSR*, **305**, 621 (1989) (*Chem. Abstr.*, **111**, 182661q 1989).

68. J. Belzner, Phd Dissertation, University of Münich, 1988.

69. D. K. Taylor, PhD thesis, Flinders University, 1993.

70. J. L. Adcock and A. A. Gakh, *Tetrahedron Lett.*, **33**, 4875 (1992).

71. E. W. Della and D. K. Taylor, *Australian J. Chem.*, **44**, 881 (1991).

72. K. B. Wiberg, S. T. Waddell and T. Sherman, *Tetrahedron Lett.*, **29**, 289 (1988).

73. D. G. Lee and M. van den Engh, *"Oxidation in Organic Chemistry"*, Part B, (W. S. Trahanovsky, ed.) Academic Press, New York, 177 (1973).

74. E. W. Della and J. Tsanaktsidis, *Australian J. Chem.*, **42**, 61 (1989).

75. E. W. Della and D. K. Taylor, *ibid.*, **43**, 945 (1990).

76. E. W. Della, C. A. Grob and D. K. Taylor, *J. Am. Chem.Soc.*, **116**, 6159 (1994).

77. E. W. Della and N. J. Head, *J. Org. Chem.*, **57**, 2850 (1992).

78. W. Adcock, G. T. Binmore, A. R. Krstic, J. C. Walton and J. Wilkie, *J. Am. Chem. Soc.*, **117**, 2758 (1995).

79. T. B. Patrick, K. K. Johri, D. H. White, W. S. Bertrand, R. Mokhtar, M. R. Kilbourn and M. R. Welch, *Can. J. Chem.*, **64**, 138 (1986).

80. W. Adcock and A. R. Krstic, *Tetrahedron Lett.*, **33**, 7397 (1992).

81. K. B. Wiberg and V. Z. Williams, *J. Am. Chem. Soc.*, **89**, 3373 (1967).

82. K. B. Wiberg and N. McMurdie, *J. Org. Chem.*, **35**, 369 (1970).

83. E. W. Della and J. Tsanaktsidis, *Australian J. Chem.*, **39**, 2061 (1986).

84. T. Janecki, S. Shi, P. Kaszynski and J. Michl, *Coll. Czech. Chem. Comm.*, **58**, 89 (1993).

85. E. W. Della, W. K. Janowski, B. Kasum, K. P. Kirkbride and N. J. Shirley, *Heteroat. Chem.*, **3**, 33 (1992).

86. R. M. Moriarty, J. S. Khosrowshahi, R. S. Miller, J. Flippen-Andersen and R. Gilardi, *J. Am. Chem. Soc.*, **111**, 8943 (1989).

(Received February 27, 1996)