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STEREOCHEMICAL FEATURES OF THE (2 + 2) CYCLOADDITION REACTIONS OF CHIRAL ALLENES. V. CYCLOADDITION OF 1-*TERT*-BUTYL-3-METHYLALLENE WITH 1,1-DICHLORO-2,2-DIFLUOROETHENE

DANIEL J. PASTO* AND JOHN BROPHY

Department of Chemistry and Biochemistry, University of Notre Dame, Notre Dame, Indiana, 46556, U.S.A.

The (2 + 2) cycloaddtion reactions of 1-*tert*-butyl-3-methylallene (*t*BMA) with radicophiles were investigated. The attempted cycloaddition reactions with *N*-phenylmaleimide, acrylonitrile and methyl acrylate produce only (4 + 2) cycloadducts of 1-*tert*-butyl-1,3-butadiene which is formed by the more rapid [1.3]hydrogen sigmatropic rearrangement of the *t*BMA. The (2 × 2) cycloaddition of *t*BMA with 1,1-dichloro-2,2-difluoroethene (1122) occurs more rapidly than does the sigmatropic rearrangement, and produces a mixture of the four cycloadducts 1–4. The cycloaddition of 1122 with enantioenriched *t*BMA produces one cycloadduct (3) in which *ca* 91% of the enantiomeric excess (ee) of the *t*BMA is transferred to the cycloadduct. The other three cycloadducts are formed retaining much less of the ee of the starting *t*BMA. The results are interpreted on the basis of molecular modeling calculations carried out on the 1122–1,3-dimethylallene system reported previously. It is suggested that cycloadduct 3 is formed by essentially only one continuous minimum-energy reaction pathway, while cycloadducts 2 and 4 are formed by two competitive minimum-energy reaction pathways which result in the formation of cycloadducts possessing opposite absolute configurations. The combined contributions of the two competitive pathways result in much lower overall degrees of transfer of the ee of the *t*BMA to the diradical intermediates and cycloadducts.

INTRODUCTION

A detailed discussion of the stereochemical features of the two-step, diradical-intermediate cycloaddition reactions of chiral allenes with 1,2- and 1,1-di- and monosubstituted radicophiles was presented in the first paper in this series,[1] and the results of the stereochemical studies on the [2 + 2] cycloaddition reactions of enantioenriched 1,3-dimethylallene with monosubstituted[1] and 1,2-[2] and 1,1-disubstituted[3] radicophilic alkenes have been described. In these cycloaddition processes considerable transfer of the enantiomeric excess (ee) of the 1,3-dimethylallene to the diradical intermediates and on to the cycloadducts is observed. In this paper, the results of a study of the [2 + 2] cycloaddition reactions of 1-*tert*-butyl-3-methylallene (*t*BMA) with various radicophiles are described.

The reactions of *t*BMA with *N*-phenylmaleimide, acrylonitrile, methyl acrylate and 1,1-dichloro-2,2-difluoroethene (1122) were investigated. With the first three radicophiles the [1.3]hydrogen sigmatropic rearrangement of *t*BMA to 1-*tert*-butyl-1,3-butadiene[4] occurs more rapidly than does diradical intermediate formation resulting in (2 + 2) cycloadduct formation. The resulting 1-*tert*-butyl-1,3-butadiene undergoes (4 + 2) cycloaddition with the dienophilic alkenes. The greater reactivity of 1122 toward diradical intermediate formation compared to the other radicophiles allowed for the predominant formation of (2 + 2) cycloaddition products with *t*BMA, and a stereochemical study of the cycloaddition of 1122 with enantioenriched (*R*)-*t*BMA was undertaken.

RESULTS

The reaction of *t*BMA with 1122 was carried out in sealed tubes with excess 1122 at 160 °C for 48 h cleanly producing a mixture of the five products **1–5**. The averaged relative yields are given in parentheses below the structures. The mixture of products was cleanly separated by preparative GLC. The ^{1}H NMR chemical shift

* Author for correspondence.

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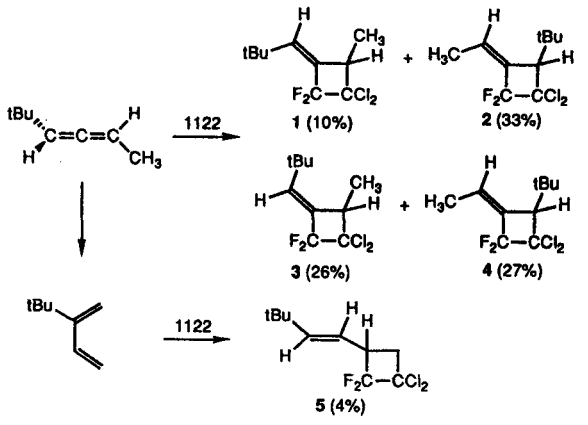


and coupling constant assignments of the cycloadducts, derived from extensive decoupling experiments, are given in Table 1.

Cycloadducts **1** and **3** were readily distinguishable from **2** and **4** by the appearance of the vinyl proton resonances which indicated vicinal coupling to a methyl group in **2** and **4** and only long-range allylic coupling to H1, and F-1 and F-2, in **1** and **3**. The stereochemistry of the four (2 + 2) cycloadducts **1**–**4** was assigned on the basis of previously observed trends in long-range shielding effects, and long-range H–H and H–F coupling constants observed in other substituted allene–1122 cycloadducts.[3,5] Distinction between **1** and **3** and between **2** and **4**, is based on the general trend that vinyl and allylic protons appear at lower field when *syn* to the CF_2 group (*ca* 0·4 and 0·1–0·2 ppm respectively) in 1122 cycloadducts.[5] These stereochemical assignments are supported by the relative magnitudes by the long-range coupling constants between H-1 and H-2 and between H-1 and the vinyl-methyl group, the *cis*-allylic coupling constants being larger than the *trans*-allylic coupling constants and the *trans*-homoallylic coupling constants being larger than the *cis*-homoallylic coupling constants.[6]

The structure of **5** was immediately apparent from the appearance of two vinyl protons in the NMR spectrum. The *trans* stereochemistry is assigned on the basis of the large vicinal coupling constant of 15·58 Hz. Cycloadduct **5** is formed by the (2 + 2) cycloaddition of 1122 to 1-*tert*-butyl-1,3-butadiene formed by the competitive [1.3]hydrogen sigmatropic rearrangement of *t*BMA.[4] The (2 + 2) cycloaddition of 1122 to substituted 1,3-butadienes in this manner is a well known process.[7,8]

Table 1. NMR chemical shifts and coupling constants of **1**–**4**[a]

	Chemical shifts			
	1	**2**	**3**	**4**
tert-Butyl	1·13	1·11	1·14	1·15
CH_3	1·27	1·40	1·93	1·82
H-1	3·28	3·53	3·25	3·31
H-2	5·65	6·09	5·93	6·34
F-1	51·8	57·0	57·3	57·2
F-2	45·6	50·7	56·7	57·1
	Coupling constants (Hz)			
	1	**2**	**3**	**4**
CH_3–H-1	6·83	7·38	2·85	1·93
CH_3–H-2	—[b]	—[b]	7·18	7·28
CH_3–F-1	0·93	0·98	2·80	3·03
CH_3–F-2	0·79	1·60	2·80	3·03
H-1–H-2	2·66	2·14	2·98	2·81
H-1–F-1	2·50	1·57	3·58	0·91
H-1–F-2	—[b]	1·75	1·07	4·10
H-2–F-1	1·02	4·03	1·50	2·80
H-2–F-2	0·84	1·98	1·50	2·80
F-1–F-2	203	192	169	93

[a] Atom specifications are indicated in the conformations of **1**–**4**.
[b] Less than 0·3 Hz.

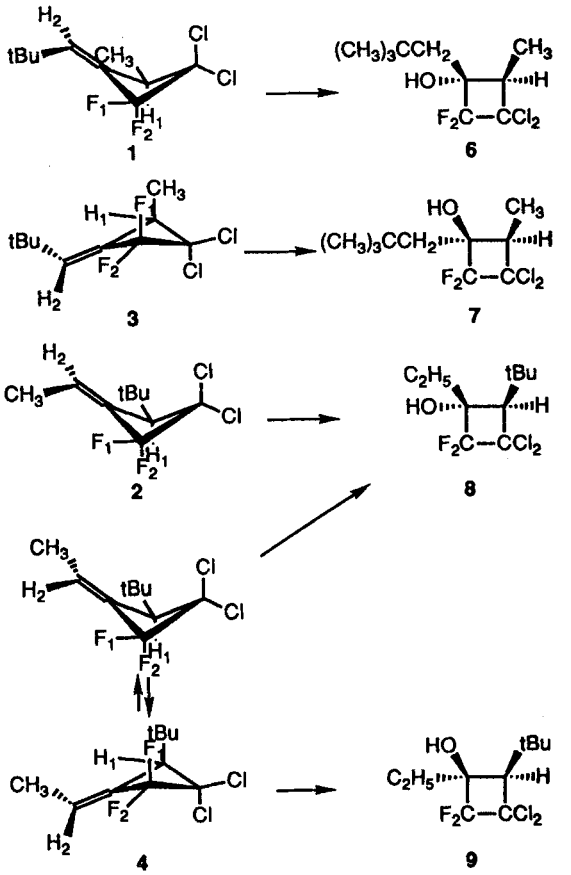


Table 2. Enantiomeric excesses (%) of starting *t*BMA and the hydroboration products **6**–**9** derived from cycloadducts **1**–**4**

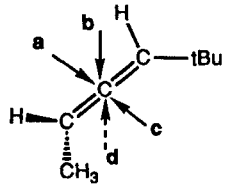
Structure	Alcohol	Run 1	Run 2
*t*BMA	—	47·1	47·1
1	**6**	—[a]	16·5
2	**8**	9·2	8·7
3	**7**	41·4	44·2
4	**8,9**	13·7	12·0

[a] Could not be measured owing to the small amount of material available.

The ee values of the cycloadducts **1**–**4** derived from enantioenriched (*R*)-*t*BMA could not be determined directly by the use of any available chiral NMR chemical shift reagent. Similarly to the procedures required in our earlier stereochemical studies on the cycloaddition reaction of 1122 with enantioenriched 1,3-dimethylallene (13DMA),[3] treatment of each of the individual cycloadducts with a large excess of borane–THF followed by oxidation resulted in the formation of stereoisomerically related tertiary alcohols. Cycloadducts **1**–**3** produced single pure alcohols assigned structures **6**–**8**, while cycloadduct **4** produced a mixture of the alcohols assigned structures **8** and **9**. The stereochemistry of the stereoisomeric aicohols has been assigned on the basis of the approach of the borane to the *exo* face of the double bond of the lowest energy conformation of the alkylidenecyclobutane as indicated by the results of molecular mechanics and *ab initio* calculations on 2-methylmethylenecyclobutane and the (*E*)- and (*Z*)-isomers of 2-methylethylidenecyclobutane.[5] On the basis of the prior calculations the predominant, lowest energy conformations of **1**–**3** are those shown which on *exo* attack of borane followed by oxidation results in the formation of the single stereoisomers shown in structures **6**–**8**. (Absolute configurations are not implied in the conformations of **1**–**4** and the structures **6**–**8** as shown.) In cycloadduct **4** the severe steric interaction between the vinyl methyl and *tert*-butyl group when the latter is in the pseudo-equatorial orientation must result in a considerable population of the pseudo-axial *tert*-butyl conformation leading to the formation of alcohol **9**. The ee values of the alcohols **6**–**9** could be readily determined by the use of a chiral NMR shift reagent (see Experimental). The results of two runs are given in Table 2.

DISCUSSION

The formation of four stereoisomeric cycloadducts was unexpected. It was anticipated that the approach of 1122 to the *t*BMA would occur essentially only to the face of the methyl-substituted double bond of the allene chromophore opposite the bulky *tert*-butyl group as illustrated in **10** (approach a) with the rotation of the methyl group toward the approaching 1122 to produce **11** predominating over the rotation of the methyl group away from the approaching 1122 to produce **12**. Rotation of the methyl group toward the approaching 1122 is slightly favored in the (2 + 2) cycloaddtion reaction of 1122 with 1,3-dimethylallene,[3] and should be even more favored in the reaction of 1122 with *t*BMA because of the very severe steric congestion between the methyl and *tert*-butyl groups in **12**. The ring closure of **11** can only produce cycloadducts having the *E* stereochemistry about the *tert* butyl-substituted exocyclic double bond and the *Z* stereochemistry about the methyl-substituted double bond in the cycloadducts. The formation of **1** having the *Z* stereochemistry at the *tert*-butyl-substituted double bond requires the intermediacy of diradical intermediate **13** and/or **14**. Intermediate **13** can be formed either by approach of the 1122 to the more sterically hindered face of the methyl-substituted double bond (approach c), or by approach of the 1122 to the more sterically hindered face of the *tert*-butyl-substituted double bond (approach d) with rotation of the *tert*-butyl group toward the approaching 1122. Neither of these two approaches seem to be sterically feasible. Intermediate **14** can be formed by approach of the 1122 to the least sterically hindered face of the *tert*-butyl-substituted double bond (approach b) with rotation of the *tert*-butyl group toward the approaching 1122. Based on the stereochemical



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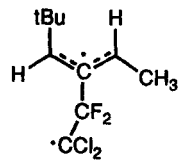

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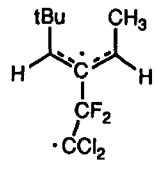

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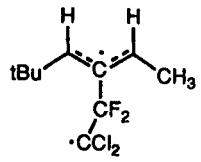

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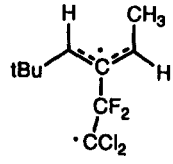

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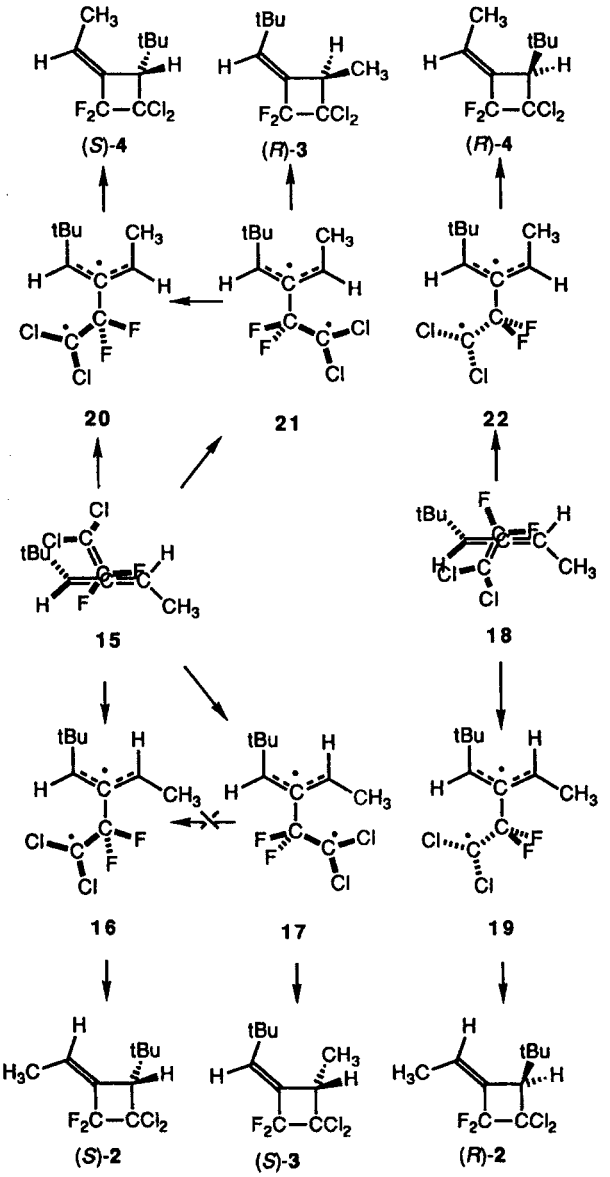
results of the earlier studies this process would appear to be the most feasible for the ultimate formation of **1**. Molecular modeling calculations have not been carried out on *tert*-butyl-containing model systems, and no further discussion of the details involved in the formation of **1** will be given. Below we shall discuss the stereochemical details involved in the formation of the diradical intermediates, the conformations of the diradical intermediates and mode of ring closure, the absolute configurations of the cycloadducts, and the relative magnitudes of the ee of the cycloadducts **2**–**4**.

Molecular modeling calculations were carried out on model systems to determine the lowest energy pathways for the formation of the *anti,anti* and *anti,syn* diradical intermediates in the cycloaddition reaction of 1122 with (*S*)-13DMA, and on the conformational energy surface of the *anti,anti* and *anti,syn* diradicals.[3] The results of these molecular mechanics calculations would be equally applicable to the 1122–(*R*)-*t*BMA system. (The presence of the *anti-tert*-butyl group in place of an *anti*-methyl group should have little effect on the calculated energy surfaces.) Based on the results of the earlier calculations,[3] the lowest energy approach of the 1122 to (*R*)-*t*BMA is that shown in **15** in Scheme 1. The continuation of this approach with rotation of the methyl group toward the approaching 1122 leads directly to the *anti,syn*-diradical intermediate **16**, one of the minimum energy conformations of **11**. The least-motion ring closure results in the formation of (*S*)-**2**. A slight clockwise rotation of the 1122 during the approach to the *t*BMA results in the formation of the *anti,syn* diradical intermediate **17**, another minimum-energy conformation of **11**. The least-motion ring closure of **17** results in the formation of (*S*)-**3**. Based on the interpretation of the results derived from the stereochemical studies on the cycloaddition reaction of 1122 with enantioenriched 13DMA,[3] the formation of the *anti,syn* stereochemistry in the diradical intermediates is expected to dominate. As will become evident later in this discussion, this is the only reasonable pathway for the formation of **3**.

The second lowest energy approach of the two reactants is shown in **18**, which upon rotation of the methyl group toward the approaching 1122 leads directly to the minimum-energy conformation of **11** having structure **19**. The direct least-motion ring closure of **19** results in the formation of **2** having the *R* configuration. Hence there are two competitive pathways for the formation of **2**, one via approach **15** and diradical intermediate **16** producing the *S* configuration, and one via approach **18** and diradical intermediate **19** producing the *R* configuration. The operation of these two pathways for the formation of **11** will result in a lower overall degree of transfer of the ee of the starting *t*BMA to cycloadduct **2**. Because the pathway via **15** and **16** is calculated to be lower in energy, it is predicted that the predominant enantiomer of cycloadduct **2** will possess the *S* configuration. (The results of molecular modeling calculations on the acrylonitrile–1,3-dimethylallene system have correctly predicted the absolute configurations observed in the cycloadducts.)[1]

The rotation of the methyl group away from the approaching 1122 in **15** directly produces the minimum-energy conformation of the *anti,anti*-diradical intermediate **20**. This same approach, by a slight rotation of the 1122, can also lead to the formation of the



Scheme 1

minimum-energy conformation of the *anti,anti* diradical intermediate **21**. The least-motion ring closure of **20** results in the formation of **4** having the *S* configuration. The least-motion ring closure of **21** would result in the formation of **3** having the *R* configuration. However, this mode of ring closure is not a favorable process. The results of earlier studies on the (2 + 2) cycloaddition of 1122 with monoalkyl-substituted allenes showed that the tendency for ring closure to the alkyl-substituted end of the allyl radical portion of the diradical intermediates increases with increasing size of the alkyl group.[9] This was attributed to the greater relief in steric strain when the alkyl group ended up attached to the C—C single bond compared to when attached to the C—C double bond.[9] During the ring closure of **21** to form (*R*)-**3** the C—C bond of the allyl radical bearing the *tert*-butyl group undergoes a shortening with an increase in steric strain in the formation of cycloadduct **3**. In contrast, the ring closure of **28** to (*S*)-**4** results in a lengthening of the C—C bond of the allyl radical bearing the *tert*-butyl group resulting in a decrease in steric congestion in forming cycloadduct (*S*)-**4**. It is suggested that the higher energy barrier for the ring closure of **21** to (*R*)-**3** allows for the competitive conformational isomerization of **21** to **20**, which then undergoes ring closure to (*S*)-**4**. A similar conformational isomerization of **17** to **16** is not expected to be competitive with ring closure owing to the higher energy barrier for rotation of one of the fluorine atoms or the dichloromethyl radical center past the *syn* methyl group. Thus, the pathway via approach **15** and diradical intermediate **17** appears to be the only reasonable pathway for the formation of cycloadduct **3** possessing a predominant *S* configuration. Cycloadduct **3** is formed with a very high net degree of transfer of the ee (*ca* 91%) of the starting *t*BMA to the diradical intermediate **17** and on to cycloadduct **3**.

Cycloadduct **4** can also be formed via the lower energy approach **18** and diradical intermediate **22**. However, in this case it is formed having the *R* configuration. The considerably lower degree of retention of the ee in **4** (26%) than that observed in the formation of cycloadduct **3**, suggests that both pathways via **15** and **20** which produce (*S*)-**4** and the pathways via approach **18** and **22** to produce (*R*)-**4** contribute to the formation of cycloadduct **4**. As the pathway via **15** to **20** is calculated to be of lower energy than that via **18** to **22** in the 1122–13DMA system, the predominant enantiomer of **4** is expected to possess the *S* configuration.

CONCLUSION

The results derived from this study have provided for a much more detailed understanding of the various reaction pathways operative in product formation in the (2 + 2) cycloadditon of 1122 with 1,3-disubstituted allenes. The most impressive result is the extremely high degree of transfer of the ee of the starting *t*BMA to cycloadduct **3**. This could only be observed because of the formation of **3** by essentially only one reaction pathway. The other two major cycloadducts, **2** and **4**, however, can be formed via two different reaction pathways which produce cycloadducts having opposite absolute configurations. In view of the net degree of transfer of ee to **2** and **4** (33 and 27% respectively), the degree of transfer of the ee of the starting *t*BMA via the individual pathways must be substantially higher, and may be of the order of that observed in the formation of **3** via approach **15** and diradical intermediate **17**.

The degree of transfer of ee of the starting *t*BMA to the diradical intermediates and on to the cycloadducts is much higher than that observed in the (2 + 2) cycloaddition of 1122 with 13DMA.[3] In our initial analysis of the stereochemical aspects of the formation of the diradical intermediates with chiral allenes it was suggested that the higher intrinsic asymmetries of the diradical intermediates formed from unsymmetrically 1,3-disubstituted allenes should result in a greater degree of transfer of the ee of the starting allene to the intermediates. The present results indicate that this is indeed true. However, it must be admitted that in the 1122–13DMA system the various minimum-energy pathways producing cycloadducts having different absolute configurations might be more competitive owing to lesser long-range steric interactions in the diradical intermediates and on ring closure. Further studies are being undertaken to evaluate this aspect of the problem.

EXPERIMENTAL

Preparation of (*S*)-*3-butyn-2-ol.* (*S*)-3-Butyn-2-ol was prepared by the reduction of 3-butyn-2-one with 'Alpineborane' by the procedure of Brown and Pai.[10] The ee of the product was determined by the use of the chiral NMR shift reagent tris[3-(trifluoromethylhydroxymethylene)-(+)-camphorato]europium(III) in $CDCl_3$ solution, indicating an ee of 52·7%.

Preparation of (*R*)-*1-tert-butyl-3-methylallene.* The preparation of (*R*)-1-*tert*-butyl-3-methylallene (*t*BMA) was carried out on the mesylate of (*S*)-3-butyn-2-ol by the procedure of Elsevier and Vermeer.[11] The ee of the *t*BMA was determined by the use of a 1 : 3 mixture of the NMR shift reagents (6,6,7,7,8,8,8-heptafluoro-2,2-dimethyl-3,5-octane-dionato)silver [Ag(fod)] and chiral tris[3-(heptafluoro-propylhydroxymethylene-(+)-camphorato]ytterbium (III) [$Yb(hfc)_3$] in $CDCl_3$ solution.[12] Aliquots of the Ag(fod)–$Yb(hfc)_3$ solution were added until baseline resolution of the *tert*-butyl resonances in the diastereomerically related complexes was achieved. Integration of the resulting NMR spectrum indicated an ee of the *t*BMA of 47·1%.

Reaction of (R)-TBMA with 1,1-dichloro-2,2-difluoroethene (1122). In a thick-walled Pyrex tube were placed 100 μl (0·64 mmol) of *t*BMA. The tube was cooled in a dry-ice–acetone slurry and about 1 ml of 1122 was condensed into the tube. The tube was triply freeze degassed under reduced pressure, sealed and placed in a sand-bath at 160 °C for 2 days. The tube was opened and the excess of 1122 was allowed to evaporate. The NMR spectrum of the residue showed the presence of five cycloadducts. The cycloadducts were isolated via preparative GC on an 18 ft × 1/4 in i.d. column of diethylene glycol adipate on Chromosorb P at 160 °C. The ^{1}H 300 mHz and ^{19}F (external BF_3–etherate) 500 mHz NMR spectral data are given in Table 1. ^{13}C NMR (300 mHz, $CDCl_3$): **1**, δ 145·06, 77·20, 50·94, 33·72, 30·90, 29·61, 24·23, 14·21; **2**, δ 143·83, 65·85, 52·05, 37·39, 33·86, 29·55, 17·78, 15·26; **3**, δ 130·10, 115·61, 83·28, 66·50, 34·55, 29·48, 27·62, 14·50; **4**, δ 130·27, 115·78, 83·40, 68·40, 36·09, 28·65, 27·79, 15·45 ppm. No parent ions could be detected by electron impact (EI) or chemical ionization (CI) mass spectrometry (MS). EI-MS: fragment ions at *m/z* 227 (−CH_3), 207 (−Cl), 191, 143, 115.

5: NMR (300 mHz, $CDCl_3$), δ 1·05 (s, 9H), 2·54 (dddd, *J* = 19·36, 13·03, 9·84, 9·52 Hz, 1H), 2·78 (dddd, *J* = 17·25, 13·03, 9·28, 4·20 Hz, 1H), 3·23 (dddd, *J* = 9·52, 7·34, 4·20, 1·01 Hz, 1H), 5·39 (dd, *J* = 15·58, 7·34 Hz, 1H) 5·67 (dd, *J* = 15·58, 1·01 Hz, 1H) ppm. ^{19}F NMR (relative to external BF_3-etherate), δ 8·1 (ddd, *J* = 184, 19·36, 17·25 Hz) and 16·1 (ddd, *J* = 184, 9·84, 9·28 Hz) ppm. EI-MS: no parent peak could be observed.

Hydroboration of the cycloadducts. To 15 μl (0·10 mmol) of each cycloadduct were added 5 ml of dry THF. While stirring under a nitrogen atmosphere, 210 mg (5·57 mmol) of sodium tetrahydroborate were added and stirred until completely dissolved. The mixture was cooled to 0 °C and 733 μl (7·42 mmol) of BF_3–etherate were slowly added. Stirring was continued for 24 h at room temperature and then at 0 °C. 1·5 ml of 5% sodium hydroxide was slowly added followed by 1·5 ml of 30% hydrogen peroxide. After stirring for 30 min the reaction mixture was extracted with methylene chloride. The extract was washed several times with water and dried ($MgSO_4$). The solvent was removed and the alcohols were purified by rotating disc thin-layer chromatography on silica gel using methylene chloride–hexane (50 : 50) as eluent. The NMR spectra of the reaction products indicated the formation of single alcohols **6**, **7** and **8** from cycloadducts **1–3**, and a 1 : 2 mixture of **8** and **9** from **4**.

^{1}H NMR (300 mHz, $CDCl_3$): **6**, d 0·98 (s, 9H), 1·14 (dd, *J* = 7·56, 1·55 Hz, 3H), 1·80–2·00 (m, 2H), 3·00–3·10 (m, 1H), 4·80 (d, *J* = 5·60 Hz, 1H); **7**, d 0·97 (d, *J* = 0·70 Hz, 9H), 1·30 (d, *J* = 6·91 Hz, 3H), 1·76 (dt, *J* = 18·77, 1·89 Hz, 1H), 1·78 (d, *J* = 18·77 Hz, 1H), 2·38 (qt, *J* = 6·91, 2·18 Hz, 1H), 4·85 (d, *J* = 5·68 Hz, 1H); **8**, d 1·09 (dt, *J* = 7·30, 1·10 Hz, 3H), 1·22 (s, 9H), 2·05 (m, 1H), 2·16 (m, 1H), 2·43 (dd, *J* = 2·24, 1·50 Hz, 1H), 2·59 (dd, *J* = 4·83, 3·53 Hz, 1H); **9**, d 0·98 (t, *J* = 7·37, Hz, 3H), 1·18 (s, 9H), 1·75 (m, 1H), 2·06 (m, 1H), 2·42 (t, *J* = 2·50 Hz, 1H), 5·05 (d, *J* = 5·58 Hz, 1H). No parent ion could be detected by EI-MS or CI-MS. EI-MS: fragment ions at *m/z* 209, 193, 173, 157.

Determination of the enantiomeric excesses of Alcohols 6–9. Aliquots of a solution of 50 mg (0·056 mmol) of tris[3-(trifluoromethylhydroxymethylene)-(+)-camphorato]europium(III) [$Eu(tfc)_3$] dissolved in 500 μl of $CDCl_3$ were added to the NMR solutions of the alcohols until near baseline resolution of either the methyl or *tert*-butyl resonances was achieved. The enantiomeric excesses were calculated (±10% error) by the peak simulation program GENCAP on a GE NMR Data Station. The ee values are listed in Table 2.

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REFERENCES

1. D. J. Pasto and K. D. Sugi, *J. Org. Chem.* **56**, 3795–3801 (1991).
2. D. J. Pasto and K. D. Sugi, *J. Org. Chem.* **56**, 6216–6224 (1991).
3. D. J. Pasto and K. D. Sugi, *J. Org. Chem.* **57**, 12–17 (1992).
4. D. J. Pasto and J. Brophy, *J. Org. Chem.* **56**, 4554–4556 (1991).
5. D. J. Pasto, K. D. Sugi and J. L. Malandra, *J. Org. Chem.* **56**, 3781–3794 (1991).
6. S. Sternhall, *Rev. Pure Appl. Chem.* **14**, 15–46 (1964).
7. L. K. Montgomery, K. Schueller and P. D. Bartlett, *J. Am. Chem. Soc.* **86**, 622–628 (1964).
8. P. D. Bartlett, C. J. Dempster, L. K. Montgomery, K. E. Schueller and G. E. H. Wallbillich, *J. Am. Chem. Soc.* **91**, 405–409 (1969).
9. D. J. Pasto and S. E. Warren, *J. Am. Chem. Soc.* **104**, 3670–3676 (1982).
10. H. C. Brown and G. G. Pai, *J. Org. Chem.* **50**, 1384–1394 (1985).
11. C. J. Elsevier and P. J. Vermeer, *J. Org. Chem.* **54**, 3726–3730 (1989).
12. A. Mannschreck, W. Munninger, T. Burgemeister, J. Gore and B. Cazes, *Tetrahedron* **42**, 399–408 (1986).