Alkylation of benzene with cyclic ethers in superacidic media

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Superacidic trifluoromethanesulfonic acid (triflic acid, TFSA) catalyzes the alkylation of benzene with various cyclic ethers. The characteristic products formed in the reaction of highly reactive oxiranes (methyloxirane, styrene oxide, and cyclohexene oxide) are phenyl-substituted compounds formed as a result of Friedel–Crafts-type mono- and dialkylation. Oxetanes (2-isopropyloxetane) and oxolanes (tetrahydrofuran, 2,5-dimethyltetrahydrofuran, 2,2,5,5-tetramethyltetrahydrofuran), in turn, undergo electrophilic cyclialkylative ring closure (cyclialkylation) to form mainly bicyclic compounds (tetralin, dihydronaphthalene, and naphthalene derivatives). In the majority of cases, alkylated products can be isolated in good to reasonable yields. Reactivity of cyclic ethers, product formation and product distributions are interpreted by taking into account ring strain, acidity of reaction mixtures and stability of carbocationic intermediates.

KEY WORDS: Friedel–Crafts alkylation; cyclialkylation; triflic acid; cyclic ethers; acidity dependence.

1. Introduction

Friedel–Crafts alkylation of aromatics [1,2], an important carbon–carbon bond-forming reaction, is still a topic of great interest from both theoretical and practical points of view. Recent research interests include the exploration of new, recyclable solid materials with improved catalyst performance [3] and the search for new, uncommon alkylating agents, such as carbonyl compounds [4–10]. Ionic liquids [11,12] and the water-tolerant, recyclable triflate salt catalysts (scandium triflate and lanthanum triflates) [13–15] have also been tested.

The use of cyclic ethers as alkylating agents are hardly explored even though it allows the synthesis of aryl-substituted alcohols. The process called *hydroxyalkylation* is of practical significance in the preparation of various fragrances. 2-Phenylethanol, an important fragrance chemical, for example, is manufactured by the hydroxyalkylation of benzene, with ethylene oxide applying a stoichiometric amount of $AlCl_3$ [16]. The few observations on the alkylation with oxiranes [17], oxetanes [18,19] and oxolanes [20] show that these transformations, in general, are promoted by excess Lewis acids and usually characterized by high stereospecificity. This latter feature of the process is in sharp contrast with that of alkylation with chiral dialkyl ethers resulting in complete racemization.

The alkylation of benzene with (+)-methyloxirane in the presence of $AlCl_3$ or $SnCl_2$ in carbon disulfide yields (+)-2-phenylpropan-1-ol with 95% retention of configuration [17]. The reaction of benzene and (+)-2-methyltetrahydrofuran catalyzed by $AlCl_3$ results in 35% inversion [20]. Varying degrees of inversion were also observed in the alkylation of benzene with (+)-2-methyloxetane: $SnCl_4$ and $TiCl_4$ showed moderate stereoselectivity (20% inversion), whereas about 60% inversion was detected in the process promoted by $AlCl_3$ [19]. The high degree of retention observed was interpreted by the S_N2 mechanism, whereas decreased stereoselectivity was attributed to the involvement of carbocationic intermediates in the process.

A variation of the transformation is the intramolecular ring closure of aralkyl-substituted cyclic ethers called *cyclialkylation*. Arylalkyl epoxides were found to yield hydroxylated products selectively [21,22]. The ring closure of 2-(3-phenyl-1-propyl)-oxiranes invariably gives the corresponding six-membered ring compounds, i.e., tetralin derivatives are formed. Again, the use of Brønsted or Lewis acids in stoichiometric amounts or in excess is usually necessary. The synthesis of hydroxyalkyl-substituted tetralins may also be accomplished by reacting 2-(3-phenyl-1-propyl)-tetrahydrofurans and tetrahydropyrans in the presence of $TiCl_4$ [23]. Cyclialkylation was shown to be stereoselective.

It is of interest to note that attempts to use solid acids in intermolecular alkylation with oxiranes failed to yield alkylated products [24]. Instead, oligomerization took place. In a recent paper, alkylation of 2-methoxynaphthalene with propylene oxide using titanium beta molecular sieve was reported to proceed, though in low yield (less than 8% of C-alkylated products) [25]. In marked contrast, cyclialkylation was found to be feasible by reacting arylalkyl epoxides over solid acids such as Nafion-®H [26] or zeolites and clays [24,27].

As part of an ongoing study on the use of various electrophilic catalysts in organic transformations, we are

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interested in the Friedel–Crafts alkylation with unusual alkylating agents in superacidic media. We have recently reported on the alkylation of aromatics with diols in superacidic trifluoromethanesulfonic acid (triflic acid, TFSA) [28]. Here we disclose our results of a comprehensive study with respect to the Friedel–Crafts alkylation of benzene with a series of substituted cyclic ethers of varying ring sizes in the presence of triflic acid.

2. Experimental

General. Triflic acid (3M Company), trifluoroacetic acid (Aldrich, 99%), decane (Aldrich, 99%), methyloxirane (Ferak, 99%), styrene oxide (Aldrich, 97%) and cyclohexene oxide (Fluka, 99%) were commercial products and were used without further purification. 2-Isopropyloxetane studied was prepared for earlier studies [30]. Tetrahydrofuran (99.8%) and 2,5-dimethyltetrahydrofuran (98%, isomeric mixture) were purchased from Fluka, whereas 2,2,5,5-tetramethyltetrahydrofuran was synthesized by the dehydration of the corresponding diol in the presence of polyphosphate ester (PPE) (98% purity by GC). Benzene was purified and dried by standard methods.

General procedure. Reactions were carried out in a 15-mL vial with a side-neck equipped with a magnetic stirrer and a condenser under argon. A mixture of the cyclic ether and benzene was added in 10 min to an appropriate amount of triflic acid (or a mixture of TFSA and TFA), kept at 0 °C. The mixture was allowed to warm up to room temperature and stirring was continued for 3 h. In a few cases, reactions were performed at 50 °C in a closed vial. The mixture was poured over ice, extracted with CH_2Cl_2 (2×25 mL), and the organic layer was washed with brine (25 mL). The product after drying (Na_2CO_3) and evaporation was subjected to gas chromotography (GC) and GC/MS analysis. For quantitative GC analysis, decane was used as internal standard. Individual product compounds were isolated by column chromatography and identified by NMR. In some cases, reactions on a larger scale were performed to obtain a larger amount of a product for spectroscopic identification.

Equilibration studies. To learn about the stability of the products under reaction conditions, in a few cases, pure compounds or reaction products were treated using a triflic acid/benzene/substrate mixture in a ratio of 45 : 10 : 1, which is the composition most often used.

Analysis. The product identification was carried out by NMR, FT-IR spectroscopies and mass spectrometry (MS). In addition, authentic samples synthesized independently were also available for comparison. ^{1}H NMR and ^{13}C NMR spectra in $CDCl_3$ solution were recorded with a Bruker AM 400 spectrometer (at 400 MHz) or a Bruker DRX 500 spectrometer (at 500 MHz) with tetramethylsilane as an internal standard, while FT-IR measurements were performed with a Mattson Genesis 1 spectrometer, in neat film. A HP 5890 GC (60-m HP-1 column) coupled with a HP 5970 mass selective detector (electron impact mode, 70 eV) was used for mass spectrometric identification. Gas chromatography to determine quantitative product composition was performed with a CHROM 5 gas chromatograph equipped with a flame ionization detector and a 30-m DB-1 column using nitrogen as a carrier gas. Column chromatography was performed with silica gel 40 (Merck, particle size 0.063–0.200 mm) using a mixture of hexane–ethyl acetate (9 : 1). In every reaction, a few minor product compounds usually in a combined yield of less than 5% could not be identified.

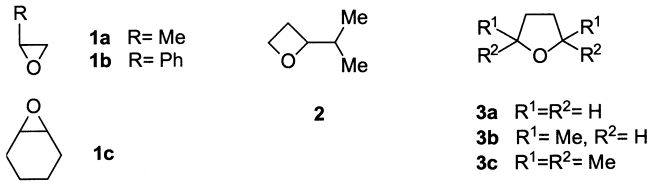
3. Results and discussion

We have studied the alkylation of benzene with oxiranes (methyloxirane, styrene oxide, cyclohexene oxide), oxetanes (2-isopropyloxetane) and oxolanes (tetrahydrofuran, 2,5-dimethyltetrahydrofuran, 2,2,5,5-tetramethyltetrahydrofuran) (scheme 1). TFSA (a non-oxidative superacid with an acidity of $H_0 = -14.1$ [6]) was chosen as the electrophilic catalyst. It has frequently been used in various alkylations [29] and found to be a useful reagent to perform Friedel–Crafts alkylations with uncommon alkylating agents providing important mechanistic information [4–10].

3.1. Transformation of oxiranes

Methyloxirane (**1a**), styrene oxide (**1b**), and cyclohexene oxide (**1c**) exhibit high reactivity in the reaction with benzene in the presence of TFSA showing complete conversion.

Detailed studies were carried out with methyloxirane (**1a**) with the aim of getting information about the effect of experimental variables on the selectivity and yield of the alkylated products. It was observed that the addition of a solution of methyloxirane in benzene to the acid was required to achieve reasonable yields of alkylated products. Reactions with various molar ratios of the three components of the reaction mixture (the acid, benzene and the oxirane) always showed complete conversion. Three characteristic groups of compounds were detected, isolated and identified by the various experimental techniques (GC, GC/MS, column chromatography, and NMR) (table 1): (i) 1,2-Diphenylpropane (**6**) and 1,1-diphenylpropane (**10**) are the two major alkylated products formed (table 1). (ii) Numerous high-molecular-weight compounds are formed in subsequent alkylation of **6** and **10**. These are isomers resulting from the reaction of three benzene and two methyloxirane



Scheme 1.

molecules. Products formed in the dehydrogenation of these compounds were also detected in minor amounts. (iii) Further by-products that could be detected by GC and GC/MS are oligomers of methyloxirane. Since these compounds are highly soluble in water, quantitative evaluation of the experimental results required the use of an internal standard. A large excess of benzene was always necessary to hinder the oligomerization process and ensure the alkylation to proceed to a satisfactory extent.

Product formation can be interpreted, on one hand, by taking into account the high reactivity of oxiranes in ring-opening reactions and, on the other hand, considering carbocation chemistry. Superacidic triflic acid is certainly capable of bringing about direct oxirane ring opening through protonation to form the cationic intermediate **4a** (scheme 2). Stabilization of this cation may occur through reaction with nucleophiles such as another methyloxirane molecule (oligomerization not shown in scheme), by further protonation (formation of dicationic species **4b**) or rearrangement to yield cation **7** stabilized by the oxygen atom. Dicationic species **4b** reacts with benzene and yields the alkylated product protonated to oxonium ion **5**. This, however, is prone to undergo further transformations. It may directly participate in a second alkylation process to form **6**. Such nucleophilic displacement by the aromatic acting as π-nucleophile is well documented in the Friedel–Crafts alkylation of primary alcohols and alkyl halides [29]. Alternatively, it gives the stable benzylic cation **8** formed as a result of a carbocationic rearrangement. Formation of this cation may also take place via the alkylation with the involvement of cation **7**. Benzylic cation **8** leads to the isomeric alkylated product **10**. It is evident that both compounds are produced in double alkylation. Moreover, they may react further in additional alkylation steps to yield products of multiple alkylation. Additional transformation possibilities are the stabilization of cation **8** through hydride transfer to form **9** and the dehydrogenation of the alkylated products to form unsaturated compounds on the action of superacidic TFSA (**11**).

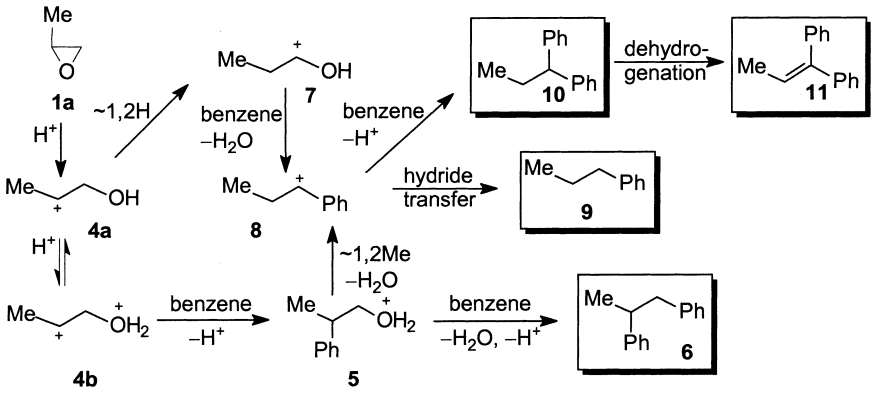
We have encountered great difficulties in achieving alkylation with styrene oxide (**1b**). A high excess of benzene was necessary to detect the formation of two alkylation products in low yields (table 2, scheme 3). It is interesting to note, that here both the monoalkylated compound bibenzyl (**12**) and the dialkylated product 1,1,2-triphenylethane (**13**) were formed. The mechanistic interpretation of the formation of these products (scheme 3) is analogous to that described in scheme 2 for methyloxirane.

Product formation in the alkylation of cyclohexene oxide (**1c**) to yield phenylcyclohexane and all four isomeric diphenyl-substituted cyclohexanes (table 3, scheme 4) is very similar to that depicted for methyloxirane. Here, cation **16** plays a key role in determining product composition. Carbocation **16**, which is formed in the dehydration of the intermediate 2-phenylcyclohexanol in a way similar to that shown for methyl-

Table 1
Alkylation of benzene with methyloxirane (**1a**)[a,b]

Entry	Composition of reaction mixture	Selectivities [%]					Yield of alkylated products [%]
	TFSA/benzene/ **1a** [mmol]	**6**	**9**	**10**	**11**	Products of multiple alkylation	
1	45 : 10 : 1	45	5	12	23	15	41
2	45 : 10 : 2	57	4	10	15	14	30
3	10 : 10 : 2	37	3	48	4	8	37
4	10 : 20 : 2	40	–	50	3	7	61
5	1 : 10 : 2	5	–	92	3	–	12
	TFSA+TFA(1 : 1)/ benzene/ **1a** [mmol]						
6	45 : 10 : 2	25	–	56	4	15	39
7	10 : 10 : 2	19	–	78	3	–	44

[a]Data presented are average values of at least two parallel experiments. Margin of error is between 5 and 10%.
[b]See also scheme 2.



Scheme 2.

oxirane (scheme 2), may be stabilized through hydride ion transfer or react in a second alkylation step with benzene to yield the two major alkylation products phenylcyclohexane (**17**) and 1,3-diphenylcyclohexane (**18**) respectively. Furthermore, it easily rearranges to all possible isomeric phenylcyclohexyl cations through hydride ion migration. These cations, upon reacting with benzene, will form the two other isomeric diphenylcyclohexanes.

Interesting changes in product distributions of oxetanes were observed by conducting acidity-dependence studies. These included the change in the avid amount used and that of the acid strength of the reaction mixture. Specifically, transformations were performed in smaller amounts of TFSA, and using a 1 to 1 molar mixture of TFSA and trifluoroacetic acid (TFA) with decreased acidity ($H_0 = -11.8$) [6] or TFA alone. These results are of importance from the mechanistic point of view.

In the transformation of oxirane **1a**, there is shift in selectivity from compound **6** to alkylated product **10** when the amount of TFSA is decreased (table 1, entries 2, 3 and 5) with a parallel significant decrease in the overall yield of the alkylated products. Decreasing acid strength results in a similar increase in the selectivity of **10** at the expense of **6** (table 1, entries 2 versus 6 and 3 versus 7). As indicated in scheme 2, changing acidity affects the equilibrium of the first intermediate cationic species **4a** and **4b**. Decreasing acidity and acid amounts shift the equilibrium further to the formation of **4a**. This means that the process involving ion **4b** present in decreasing concentrations becomes less and less significant compared with the alkylation reaction of benzylic cation **8** resulting in the formation of **10** with high selectivity under the changing reaction conditions.

When **1b** is reacted in TFA alone, only trifluoroacetates of the carbocation and alcohol intermediates (**14, 15**) could be isolated in contrast to the alkylated products (**12, 13**) formed in the acid mixture (table 2, scheme 3). The ratio of the alkylated products (higher amount of **13** versus **12**) shows that in the stronger acid mixture most of the intermediate alcohol is protonated. It is evident that this protonation equilibrium is shifted to the left in pure TFA (scheme 3) and, consequently, the corresponding intermediates (cation and the alcohol) present in high concentration are able to participate in ester-forming reactions.

3.2. Transformation of oxetanes

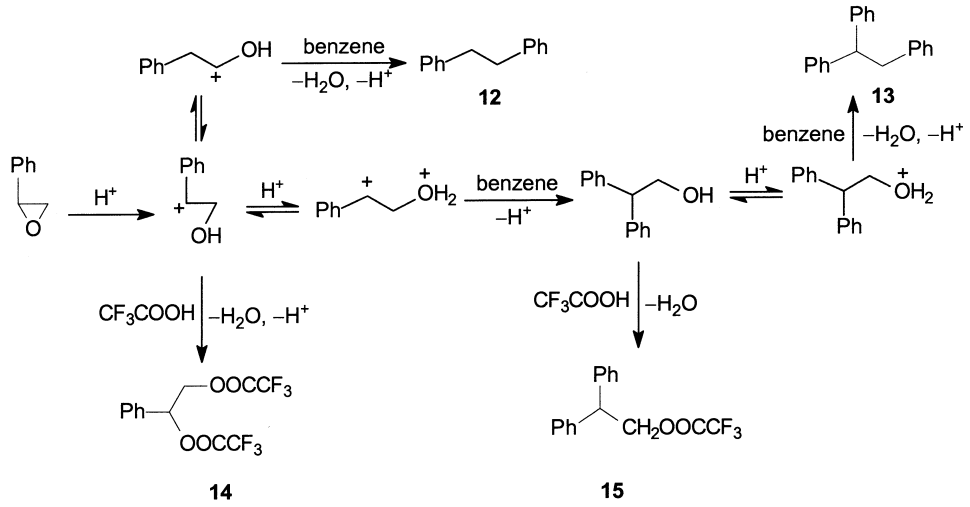
Two major types of products could be detected in the transformation of 2-isopropyloxetane (**2**) (table 4, scheme 5). These are (i) compounds formed as a result of monoalkylation (**19**) including skeletal rearrangement (**21**) and (ii) products (**22–24**), resulting from the further transformation of the intermediate protonated alcohols. The major product is the **22** tetralin derivative.

Ring opening of oxetanes upon protonation is less likely than that observed in the case of oxiranes, which is due to the smaller ring strain of oxetanes. Alkylated product **19**, therefore, may be formed through a borderline S_N2 mechanism by the attack of nucleophilic benzene to the α-carbon of the *O*-protonated ring

Table 2
Alkylation of benzene with styrene oxide (**1b**)[a]

Composition of reaction mixture	Selectivities [%]				Yield of alkylated products [%]
TFSA+TFA(1 : 1)/benzene/**1b** [mmol]	**12**	**13**	**14**	**15**	
45 : 20 : 1	35	65	–	–	5
TFA/benzene/**1b** [mmol]					
45 : 20 : 1	–	–	38	62	8

[a]See also scheme 3.



Scheme 3.

followed by secondary transformations of the intermediate protonated alcohol (scheme 5). Direct ring opening, however, cannot be excluded either. When it occurs, the more stable secondary cation is formed, which easily rearranges to the **20** dication bearing the highly stable tertiary carbocation moiety. Complex carbocationic rearrangements lead to various alkylated products. The relative importance of the two ring-opening processes can be estimated by calculating the combined selectivities of the corresponding final products, namely, those of **19** (0–27%) versus all the other compounds (**21–24**, 65–100%). It is evident that direct ring opening is still a major transformation direction as compared to that occurring with the participation of benzene via an S_N2 mechanism. A similar comparison for compounds **21–23** and **24** (53–100% versus 7–12%) shows that the major products are formed with the involvement of the more stable tertiary carbocationic intermediate **20**.

As discussed, direct ring opening is the dominant process under the most acidic conditions (table 4, entry 1). When weaker acid strength is applied, a further increase in selectivity to the products formed through direct ring opening is observed (entries 1 versus 3). This change is possibly caused by the decreasing concentration of intermediate **20**. The consequence is that its contribution to the formation of **19** decreases, whereas the formation of the other alkylated products (**22** and **24**) can still occur through the non-protonated alcoholic intermediates (not shown). An even more significant change is brought about by applying lower acid amounts, namely, alcohol **21** (entries 1 versus 2) or its trifluoroacetate (**23**) is formed (entries 3 versus 4). This is caused by the fact that under these conditions alcohol **21** is not completely protonated and, therefore, the alcohol itself is isolated and it can participate in ester formation.

Compounds **22** and **24** are unique products. These are formed from the corresponding protonated alcohols (oxonium ions) in an intramolecular alkylation process called *cyclialkylation*. The participation of the corresponding primary carbocations in this process is unlikely. Instead, ring closure may take place through the intramolecular attack of benzene to the carbon bearing the protonated hydroxyl group.

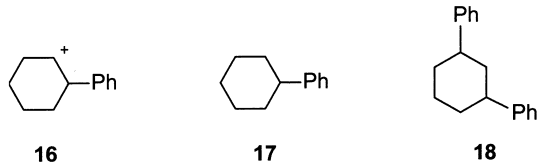
3.3. Transformation of oxolanes

The major transformation direction in the alkylation of benzene with oxolanes is cyclialkylation to form bicyclic and tricyclic partially saturated naphthalene and

Table 3
Alkylation of benzene with cyclohexene oxide (**1c**)[a]

Composition of reaction mixture	Selectivities [%]			Yield of alkylated products [%]
TFSA/benzene/**1c** [mmol]	**17**	**18**	Other isomeric diphenylcyclohexanes	
45 : 10 : 1	25	58	17[b]	64
11 : 10 : 1	12	83	5	44
2 : 10 : 1	20	60	20	22

[a]See also scheme 4.
[b]1,1-, 1,2 and 1,4-diphenylcyclohexanes in a ratio of 1 : 3 : 2.



16 17 18

Scheme 4.

anthracene derivatives as the major products. Of the three compounds studied, tetrahydrofuran (**3a**) is unique in exhibiting very low reactivity in the production of alkylated products (**25–27**) in low yield (table 5, scheme 6). An unexpected non-alkylative product, sulfone **28**, was also isolated in this reaction. This compound was shown to form during the attempted alkylation of aromatics with highly unreactive 1,2-diols in an earlier study [28] and is assumed to be the product of an unknown impurity in TFSA.

The reactivity of the symmetrically disubstituted **3b** derivative is higher than that of **3a** but it still required elevated temperature or prolonged reaction time to attain satisfactory yields of alkylated products (table 6, scheme 7). Bicyclic compounds are dominating with a shift in selectivity to the formation of more dehydrogenated compounds (substituted dihydronaphthalene and naphthalene derivatives) with increasing time and reaction temperature.

The **42** substituted tetralin and the **45** tricyclic compounds formed respectively as a result of single or double cyclialkylation are isolated in high yield and with high selectivity in the transformation of the **3c** tetramethyl derivative (table 7, scheme 8). A decrease in the acid concentration results in a decrease in the yield of the alkylated products.

Since the oxolane ring is practically free of any ring strain, direct ring opening upon protonation is unlikely. Moreover, the less-substituted **3a** and **3b** oxolane derivatives would lead to primary and secondary carbocationic intermediates of low stability. These two compounds, therefore, are likely to undergo ring opening through the attack of a nucleophile to the α-carbon of the *O*-protonated ring. This can be another oxolane molecule, thereby initiating a polymerization process. Indeed, polymer formation was observed as the main transformation direction for tetrahydrofuran (**3a**). Alkylative ring opening, in turn, is brought about by the attack of the less nucleophilic benzene through a borderline S_N2 mechanism. The significant difference found between the yields of alkylated products of **3a** and **3b** reflects the competition of these two mechanisms.

The interpretation of product formation is given in scheme 7 by depicting the various transformation pathways of the **3b** disubstituted derivative. The primary alkylation product phenylhexyl cation **29** is the key intermediate of the process. This easily rearranges into various other isomeric phenylhexyl cations through methyl and hydride migrations. These may participate in hydride transfer to yield isomeric phenylhexanes (**30–34**). Alternatively, dimethyl-substituted tetrahydronaphthalins (**35, 36**) are formed in cyclialkylative ring closure. This step is analogous to that observed and discussed in the transformation of oxetane **2**. These bicyclic compounds may react further, undergoing stepwise dehydrogenation to yield dimethyl-substituted dihydronaphthalene derivatives (**37, 38**) and dimethylnaphthalenes (**39, 40**).

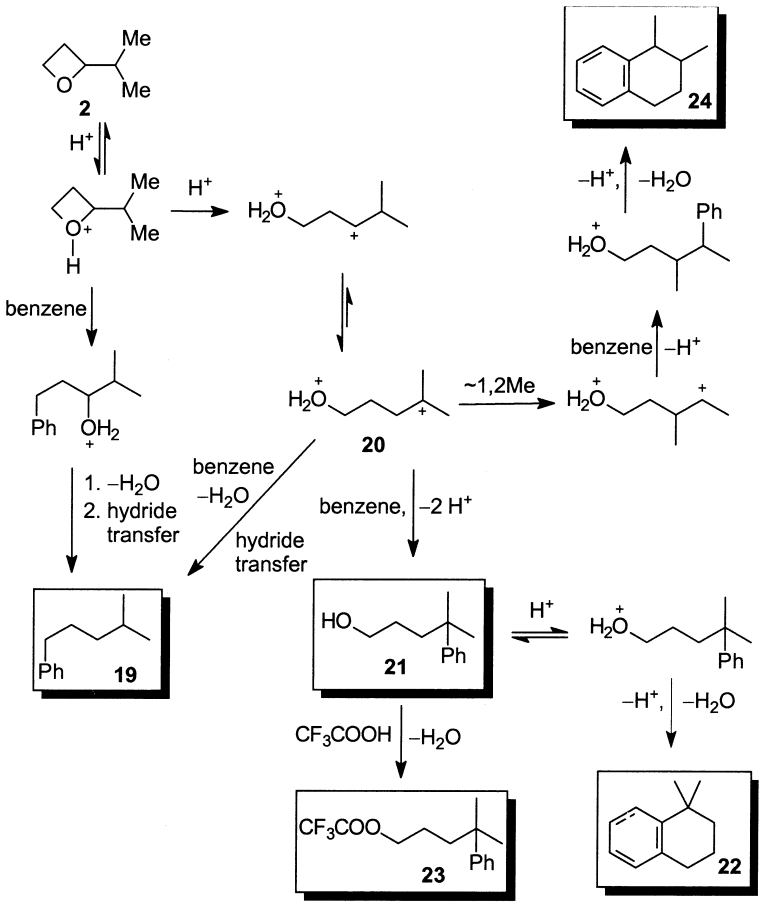
The transformation of the **3c** tetrasubstituted compound occurs similarly. A notable exception, however, is that it is likely to undergo direct ring opening upon protonation since this step leads to the **41** dication having the stable tertiary carbocation moiety (scheme 8). Rearrangement of this intermediate is unlikely and, therefore, the transformation is more selective to yield two major non-rearranged cyclialkylated products (**42, 45**) as well as a partially dehydrogenated derivative (**43**). The only compound with rearranged carbon skeleton (**44**) is formed in low yield.

Because of the low reactivity of oxolanes acidity dependence, studies could not be performed: when applying acid mixtures with weaker acid strength or using smaller amounts of acids, reactions simply did not occur.

Table 4
Alkylation of benzene with 2-isopropyloxetane **(2)**[a]

Entry	Composition of reaction mixture	Selectivities [%]					Yield of alkylated products [%]
	TFSA/benzene/**2** [mmol]	**19**	**21**	**22**	**24**	Tricyclic products	
1	45 : 10 : 1	27	–	53	12	8	51
2	10 : 10 : 1 TFSA+TFA(1 : 1)/ benzene/**2** [mmol]	8	15	70	7	–	55
3	45 : 10 : 1	15	–	75	10	–	39
4	10 : 10 : 1	–	30[b]	70	–	–	52

[a]See also scheme 5.
[b]Ester **23**.



Scheme 5.

Table 5
Alkylation of benzene with tetrahydrofuran (**3a**) (reaction time = 24 h)[a]

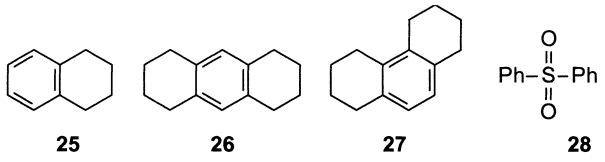
Composition of reaction mixture	Selectivity of **27** [%]			Yield of alkylated products [%]
TFSA/benzene/**3a** [mmol]	**25**	**26**	**27**	
45 : 10 : 1	100	–	–	3[b]
45 : 10 : 1[c]	42	35	23	28[d]

[a]See also scheme 6.
[b]1.5% of **28** (calculated for benzene) was also isolated.
[c]Reaction temperature = 50 °C.
[d]4% of **28** (calculated for benzene) was also isolated.

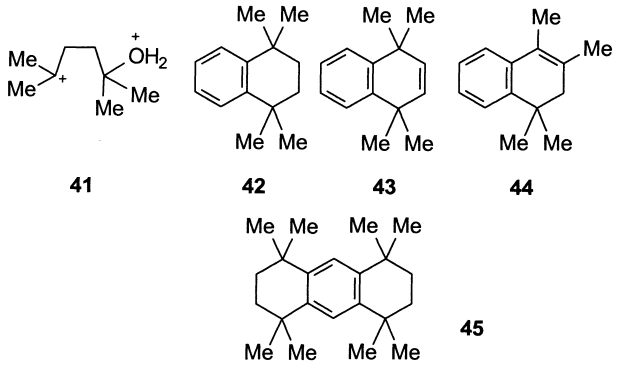
Table 6
Alkylation of benzene with 2,5-dimethyltetrahydrofuran (**3b**)[a]

Composition of reaction mixture	Selectivities [%]				Yield of alkylated products [%]
TFSA/benzene/**3b** [mmol]	Isohexyl-benzenes (**30**–**34**)	DiMetetralins (**35, 36**)	DiMedihydronaphthalenes (**37, 38**)	DiMenaphthalenes (**39, 40**)	
45 : 10 : 1	14[b]	43	7	23	41
45 : 10 : 1[c]	20[d]	39	7	33	65
45 : 10 : 1[e]	8	38	10	39	48

[a]See also scheme 7.
[b]Five compounds with 2-methyl-4-phenylpentane and 1-phenyl-3-methylpentane as major products in a ratio of 1 : 1.
[c]Reaction time = 24 h.
[d]Three compounds with 1-phenyl-2,3-dimethylbutane and 1-phenyl-3-methylpentane as major products in a ratio of 1 : 1.
[e]Reaction temperature = 50 °C.



Scheme 6.

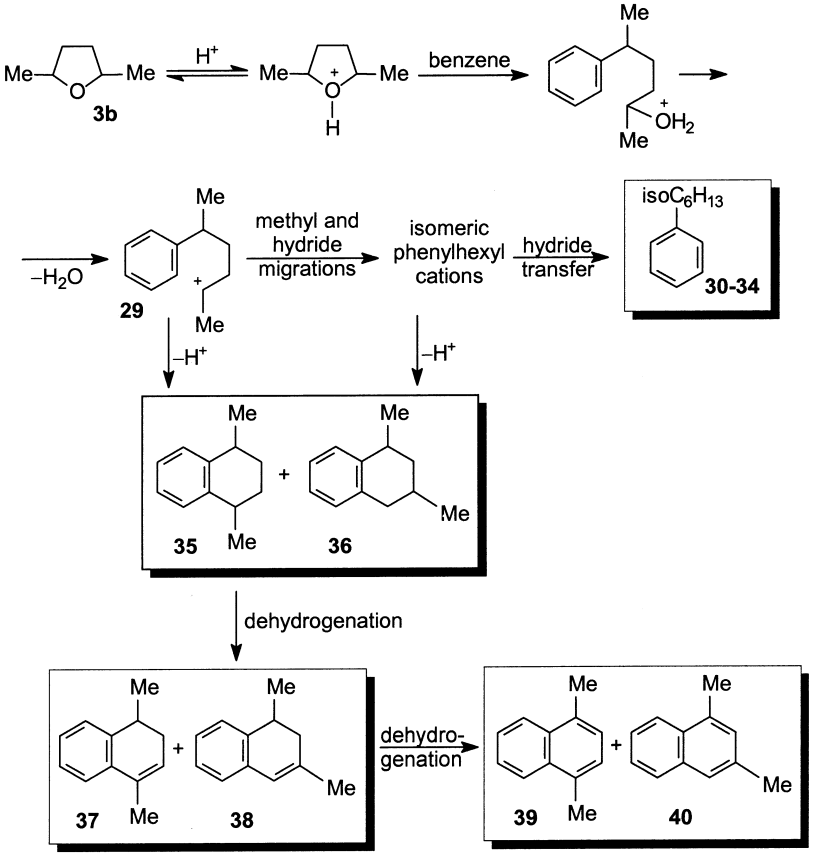


Scheme 8.

3.4. Equilibration studies

Friedel–Crafts alkylation is known to be reversible. Therefore, it is of interest to know the stability of the alkylated products under reaction conditions. Equilibration studies carried out with a product mixture formed in the reaction of 2,2,5,5-tetramethyltetrahydrofuran (**3c**) and benzene with a composition of 62% of **42** and 38% of **45** indicated only a slight change to a composition of 58 and 42%. A similar observation was also made with pure 1,2-diphenylpropane (**6**), which was transformed into a mixture containing 13% of 1,1-diphenylpropane through the more stabile 1-phenylpropyl carbocation. The 1,2/1,1 product ratios of the original alkylation reactions under similar reaction conditions are 79 : 21 and 85 : 15 (table 1). In the transformation of 1-phenylhexane, a possible product in the alkylation of benzene with 2,5-dimethyltetrahydrofuran (**3b**) (table 6), a product mixture, containing the same 5 isomers as observed in the original alkylation reaction, is formed. A comparison of the compositions (original = 5 : 40 : 45 : 5 : 5, after a 3-h equilibration = 10 : 10 : 40 : 30 : 10) indicates that the original composition is not an equilibrium mixture. A 6-h equilibration resulting in a product mixture of 40 : 2 : 58 : 0 : 0, in turn, is very close to the composition found in the 24-h reaction (45 : 5 : 50 : 0 : 0).

The transformation of 1,3-diphenylcyclohexane (**18**, 91% purity, the rest are the other three isomers), one of the products of the alkylation of benzene with cyclohexene oxide (**1c**) (table 3) was also studied. This resulted in a 1 : 1 mixture of the 1,3 and 1,4 isomers. Since the composition of the alkylation reaction (1,1, 1,2, 1,3 and 1,4 isomers formed in a ratio of 4 : 12 : 77 : 7) is quite



Scheme 7.

Table 7
Alkylation of benzene with 2,2,5,5-tetramethyltetrahydrofuran (**3c**)[a]

Composition of reaction mixture	Selectivity of **45** [%]				Yield of alkylated products [%]
TFSA/benzene/**3c** [mmol]	**42**	**43**	**44**	**45**	
45 : 10 : 1	76	**4**	–	20	100
10 : 10 : 1	54	2	5	39	64

[a]See also scheme 8.

different, in this case, the equilibrium was not reached in the alkylation reaction.

4. Conclusions

We have demonstrated that three-, four- and five-membered cyclic ethers can react with benzene to yield a wide range of alkylated products in the presence of triflic acid. These include phenyl-substituted compounds formed as a result of Friedel–Crafts-type mono- and dialkylation as well as bicyclic compounds resulting from electrophilic cyclialkylative ring closure (cyclialkylation). Because of decreasing ring strain, larger rings exhibit lower reactivity. In this case, however, alkylated products are formed in increasing yield and with higher selectivity.

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