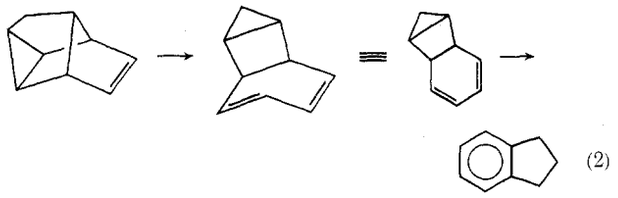
however, appears to require intolerable strain, and the most straightforward rationalization appears to involve a sequence such as that shown in eq 2.



(2)

This process requires the breaking of two carbon–carbon single bonds in addition to two hydrogen migrations, and the high conversions and low production of side products are somewhat surprising in this context. An interesting *a priori* alternative pathway, the thermally allowed[5] retro homo-Diels–Alder reaction to yield acetylene and bicyclo[2.2.1]heptadiene, is at best a minor process in this pyrolysis, even though it is apparently important in the electron impact reactions of some closely related molecules.[2]

The mechanism of the rearrangement of deltacyclene to indan is under investigation in conjunction with our study of mass spectral behavior of this series of compounds; details will be furnished in a later report.

Experimental Section

Materials. The norbornadiene dimer (hexacyclo[9.2.1.$0^{2,10}$.$0^{3,8}$.$0^{4,6}$.$0^{5,9}$]tetradec-12-ene, **2**) and deltacyclene were prepared according to published procedures.[1] Indan was purchased from Aldrich Chemical Co.

Pyrolyses. The pyrolysis of dimer **2** was carried out in an apparatus essentially the same as that described by Katz[1b,c] and by Cannell,[1a] consisting of a vertical Pyrex tube, 2.5 cm × 1 m, packed with sections of Pyrex tubing and wrapped with heating tape. The reactant was dropped into this tube from a pressure-compensated addition funnel, and the product mixture was collected in a cold trap at the bottom of the tube. A steady flow of nitrogen was maintained during the reaction. Temperatures were measured inside the apparatus with calibrated thermocouples.

Gas-phase pyrolyses were conducted in a generally similar apparatus but with a small pyrolysis tube (10 mm × 25 cm) held in a horizontal position. An inlet reservoir was arranged to allow dry nitrogen to pass directly over a small amount of liquid reactant. The concentration of reactant in the vapor mixture was controlled by cooling or warming the reservoir. The outlet was connected directly to a cold trap which was protected by a Nujol bubbler and a drying tube. After reaction, the product mixtures were warmed to room temperature and samples were injected directly into a flame-ionization gas chromatograph. For experiments with very dilute vapor, the small amount of product was generally dissolved in ether prior to gc analysis.

Preparative pyrolyses of deltacyclene were performed in the large-scale vertical apparatus and the major product was isolated by preparative gas chromatography; the product from the high-temperature, longer contact time pyrolysis of dimer **2** was isolated by fractional distillation. In both cases, the product was identical in all respects with commercial indan.

In the preparative pyrolyses, the product mixture was typically a dark brown liquid which was separable into about 80% indan and 20% viscous, high-boiling polymer. Material balances were generally in the range of 80–90%, which corresponded to yields of indan of 65–75%. In the vapor-phase pyrolyses, the total amounts of material involved were very small (of the order of a few milligrams); so material balances were difficult to determine. The product mixtures, however, appeared to contain much less polymeric material than those in the preparative liquid pyrolyses; so material balances in these systems were probably at least as high as in the preparative reactions.

Preparative gas chromatography was done on a Varian Aerograph 90-P thermal conductivity instrument using a 5 ft × 0.25 in. stainless steel column packed with 15% SE-30 on 60/80 Chromosorb W. Analytical gas chromatography was done on a Perkin-Elmer 990 flame-ionization instrument using 10 ft × 0.125 in. aluminum columns packed with 3–5% SE-30 or FFAP on 80/100 Chromosorb W.

Acknowledgment. This research was supported by grants from the Research Corporation and from the Boston University Graduate School. The mass spectrometer was purchased through a grant from the National Science Foundation.

Registry No.—1, 7785-10-6; 2, 7781-74-0; 3, 496-11-7.

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Tetrabutylammonium Fluoride. A New Reagent for the Synthesis of Hydantoins

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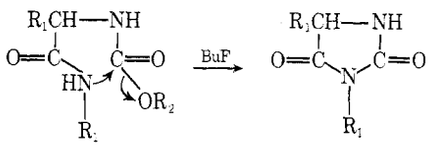
Tetraalkylammonium fluorides have been used more and more for different purposes in preparative organic chemistry in the last couple of years, for example, for the cleavage of *tert*-butyldimethylsilyl ether[1] or for the fluorination of fluoroolefins.[2] Furthermore, it proved to be a useful reagent in a number of elimination reactions.[3-5]

Results

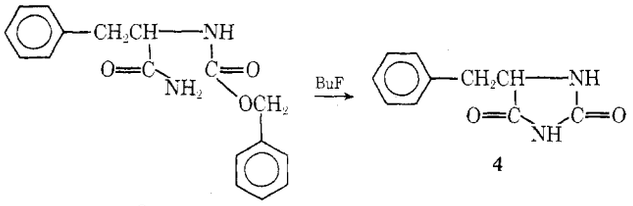
We have now found that tetrabutylammonium fluoride (BuF) has a remarkable capacity to enable intramolecular cyclizations of the following type to proceed.



1 2

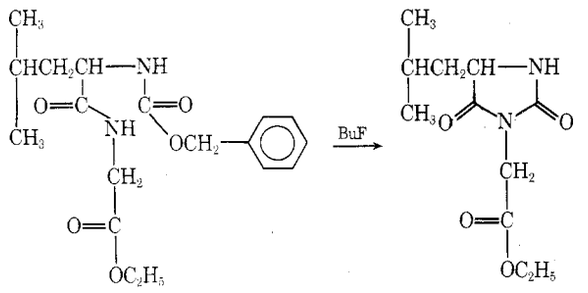
R_1 = H, CH_3, $C_6H_5CH_2$
R_2 = CH_3, $C_6H_5CH_2$

Thus in boiling tetrahydrofuran carbobenzoxyphenylalaninamide gives the corresponding hydantoin in over 90% yield.



3 4

The same reaction could be performed with a series of carbamates to produce substituted hydantoins in excellent yields. Extending this reaction to peptides we found that, *e.g.*, carbobenzoxydipeptides like Z-Leu-Gly-OEt, if exposed to BuF in THF, undergo cyclization with similar ease.



5

It is both remarkable and advantageous that BuF allows these cyclizations to take place under essentially neutral conditions. Previous methods invariably relied on strongly alkaline media; side reactions could not be avoided and the yield of the cyclized product was often very low (20–40%).

There are many—at first sight—unique features of this ring closure, in particular with regard to the polarity of the solvent and the nature of the quaternary ammonium salt.

(1) In protic solvents like alcohols or solvent mixtures containing water, cyclization does not take place.

(2) Solvents of very low polarity diminish the yield considerably.

(3) Tetrahydrofuran seems to be the solvent of choice.

(4) Cyclization is limited to the fluoride salt; salts of other anions such as tetrabutylammonium chloride or bromide do not yield any noticeable amount of hydantoin.

(5) We have found that the use of 2–3 molar equiv of BuF and refluxing for 12–14 hr represent the optimal reaction conditions.

Discussion

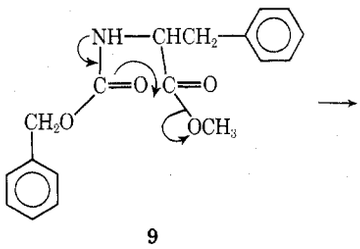
The strong proton acceptor capacity of quaternary ammonium halides is well known,[6] but this alone cannot be a sufficient explanation for this ring formation, since the bromide and chloride salts do not give hydantoins.

Thus the existence of "naked" F^- seems to be essential for cyclization and BuF is an ideal source of it. BuF is completely dissociated[7] unlike the corresponding bromide or chloride salts, even in solvents of medium polarity like tetrahydrofuran. F^- is not solvated in this solvent and represents a weak nucleophile and a strong base at the same time, facilitating certain types of base-catalyzed cyclization reactions. The role of quaternary ammonium salt would be then simply to produce the necessary amount of F^- in organic solvents. Several reactions have been reported as being catalyzed by potassium fluoride, such as the Knoevenagel reaction[8] or the cyclization of adipic acid derivatives[9] to the corresponding cyclopentanones. All of these reactions are typically base catalyzed, similarly to the hydantoin formation described in this paper.

Indirect evidence of another type of cyclization with the participation of neighboring groups has also been observed with BuF. When carbobenzoxy-L-phenylalanine methyl ester was treated with BuF under the conditions already mentioned, the only product isolated in nearly quantitative yield was carbobenzoxy-DL-phenylalanine. A possible explanation of this saponification coupled with racemization would be the formation of the corresponding azlactone intermediate, which is known to be involved in several racemization phenomena.[10]

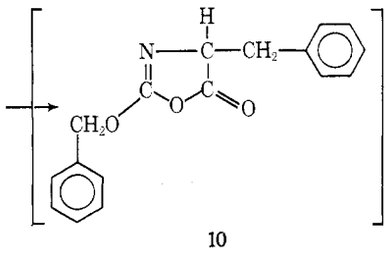
Azlactone, which is relatively unstable, could not be isolated, since it is immediately hydrolyzed by the small amount of water always present in BuF.

For this racemization reaction the same observations which regard to solvent and type of quaternary salt were valid as for the hydantoin formation.



9

Z-L-Phe-OCH_3



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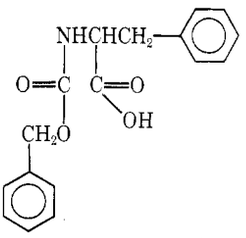

11

Z-DL-Phe-OH

The use of BuF for other base-catalyzed reactions is certainly not limited to the two SNi reaction types described here. Other applications of this reagent extending its use to those reactions which are known to be catalyzed by potassium fluoride are under study.

Experimental Section

Synthesis of BuF. Two methods are described in the literature for the synthesis of BuF,[11] but both of them are relatively complicated and time consuming. In our experience the simplest way to produce BuF is the following. A 100-ml ion exchanger Amberlite IRA 410 is transformed into the OH form on a column with dilute NaOH and washed with water until neutral. Aqueous HF is then passed through the column and finally 10 g of tetrabutylammonium bromide dissolved in 100 ml of water. After the resin is washed with water the combined water fractions are repeatedly evaporated *in vacuo* until no water is present. The resulting BuF, isolated in quantitative yield, is a colorless oil which becomes crystalline in the presence of humidity.[11]

Typical Procedure for Hydantoin Formation. *N*-Carbobenzoxyphenylalanylhomoveratrylamide (6.4 g, 13.5 mmol) and 10.6 g (40 mmol) of BuF are dissolved in 200 ml of tetrahydrofuran and refluxed for 14 hr. After partial evaporation of the solvent the product is precipitated by adding water. It is filtered and washed with water and ether. Without recrystallization 4.6 g (97%) of hydantoin is isolated, mp 157–158°, in analytically pure form.

Anal. Calcd for $C_{20}H_{22}N_2O_4$: C, 67.7; H, 6.3; N, 7.9; O. 18.1. Found: C, 67.3; H, 6.2; N, 7.7; O, 18.6.

Acknowledgment. I wish to thank Professors W. Oppolzer and E. Winterfeldt for valuable discussions and Mr. K. Lintner and Mrs. H. Tanner for their technical assistance.

Registry No.—**2** (R = $C_6H_5CH_2$; R′ = homoveratryl), 51849-51-5; *N*-carbobenzoxyphenylalanylhomoveratrylamide, 51849-52-6; tetrabutylammonium fluoride, 429-41-4.

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Fluorination with Xenon Difluoride. Fluorine Addition to 1-Phenylacetylenes

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Electrophilic addition of halogens to olefinic systems has been the subject of considerable study.[1] The analogous additions[1,2] to acetylenic systems have received much less attention. In particular, the addition of molecular fluorine,[3] chlorine monofluoride,[4] bromine monofluoride,[4,5] and iodine monofluoride[4] to acetylenes has been studied. Our recent observations that xenon difluoride adds fluorine to 1-aryl-substituted olefins[6,7] and the phenanthrene system[8] to form vicinal difluorides led us to investigate the fluorine addition to carbon–carbon triple bond with this reagent.

Although there is a structural relationship between carbon–carbon double bonds and triple bonds, the reactivities of the two systems toward electrophilic reagents are quite different. In a very recent work,[9] the rate ratio $k_{olefin}/k_{acetylene}$ of the order of 10^5 in bromination and chlorination of styrene–phenylacetylene and other olefin–acetylene pairs was observed. This difference was explained in terms of different ease of formation of carbonium ions and vinyl cations in electrophilic additions. In view of this consideration it was not certain that XeF_2 would add fluorine to 1-phenylacetylenes at all. Recently, propyne[10] was found to be resistant to fluorine addition with XeF_2 in a gas-phase reaction. After 100 days at room temperature it gave 2,2-difluoropropane in a 33% yield and at least nine other trace products. On the other hand, the addition across the triple bond might undergo accompanying substitution of the phenyl ring if one takes into account the ease of fluorination of benzene derivatives[11] with XeF_2. Therefore a study was undertaken to establish these points.

The fluorine additions to acetylenes (1) with xenon difluoride were conducted at 25° in methylene chloride with anhydrous hydrogen fluoride as catalyst. Less than stoichiometric amounts of xenon difluoride did not favor difluoro olefin formation and only tetrafluoride (2) and unreacted acetylene were found in the reaction mixture. However, the use of 2.5 equiv of XeF_2 led to the formation of 2 in over 50% yield.

$$\underset{\mathbf{1}}{PhC{\equiv}CR} + 2XeF_2 \xrightarrow[CH_2Cl_2]{HF} \underset{\mathbf{2}}{PhCF_2CF_2R} + 2Xe$$

a, R = Ph
b, R = CH_3
c, R = n-C_3H_7

The structures of previously known **2a**[3] and **2b**[3] were identified and that of unknown **2c** assigned by its ir, ^1H and ^{19}F nmr, and mass spectra.

The acetylenes seem to fluorinate completely to tetrafluoride, which implies that difluoro olefin is more reactive for fluorine addition than is the parent acetylene. The same results were found in molecular fluorine addition[3] to acetylenes at low temperature. We also observed the facile fluorine addition to 9,10-difluorophenanthrene[8] with XeF_2, yielding 9,9,10,10-tetrafluoro-9,10-dihydrophenanthrene as the reaction product.

One anomalous reaction was noted in this series of experiments. Phenylacetylene did not give 1,1,2,2-tetrafluoro-1-phenylethane, the expected product. Instead, some polymeric material was formed in this reaction.

The fluorine addition to acetylenes with XeF_2 appears to be strongly catalyzed by HF, as indicated by observation that in the absence of this catalyst reactions are very slow. We found evidence neither for the formation of fluorine-substituted products which might arise *via* a substitution fluorination of the phenyl ring nor for the presence of HF addition products, observed in the gas-phase fluorinations[10] with XeF_2. Extensive work is in progress on acid-catalyzed liquid—phase fluorination of various acetylenic systems with this reagent, which appears to be useful also for applications on a large scale.

Experimental Section[12]

Materials. The acetylenes were obtained from commercial sources and purified by vpc to conform with published physical and spectral data. Xenon difluoride was prepared by the photosynthetic method[13] and its purity was better than 99.5%. Methylene chloride was purified by the method[14] and stored over molecular sieves. Hydrogen fluoride of Fluka purum quality was used.

1,1,2,2-Tetrafluoro-1,2-diphenylethane (2a). To a solution of **1a** (0.178 g, 1.0 mmol) in methylene chloride (6 ml), xenon difluoride (0.423 g, 2.5 mmol) was added at 25° and under stirring anhydrous HF (0.100 g, 5.0 mmol) was introduced into the reaction mixture. After a few seconds the colorless solution turned dark blue and xenon gas was slowly evolved. After 6 hr gas evolution had ceased and the reaction appeared to be complete. The reaction mixture was diluted with methylene chloride (15 ml), washed (10 ml of 5% aqueous $NaHCO_3$), and dried (Na_2SO_4), and solvent was evaporated *in vacuo*. The crude product was sublimated (50°, 0.1 mm) to give **2a:** mp 121–122° (lit.[3] mp 119.3–120.5°); yield 0.163 g (64%); mass spectrum *m/e* 254 (M^+).

1,1,2,2-Tetrafluoro-1-phenylpropane (2b). To a solution of **1b** (0.116 g, 1.0 mmol) in methylene chloride (5 ml), xenon difluoride (0.338 g, 2 mmol) was added at 25° and under stirring anhydrous HF (0.02 g, 1 mmol) was introduced into the reaction mixture. After a few seconds the colorless solution turned dark blue and xenon gas was evolved slowly. After 6 hr, the reaction mixture was diluted with methylene chloride (15 ml), washed (10 ml of 5% aqueous $NaHCO_3$), and dried (Na_2SO_4), and solvent was evaporated *in vacuo*. The crude oily product was purified by vpc (6 × 0.25 in. SE-30 10% on Chromosorb A, 160°) to give **2b** as a colorless, stable liquid, yield 0.102 g (53%); mass spectrum *m/e* 192 (M^+); nmr (CCl_4) δ 1.75 (tt, 3 H, $-CH_3$, J = 19 Hz, $-CF_2CH_3$, J = 1 Hz, $-CF_2CF_2CH_3$), 7.35 (m, 5 H, Ph).

1,1,2,2-Tetrafluoro-1-phenylpentane (2c). The fluorination, work-up procedure and vpc purification were essentially the same as described for **2b. 2c** was a colorless stable liquid: yield 0.122 g (55%); high-resolution mass spectrum *m/e* 144.0931 $(M - 4F)^+$ (calcd for $C_{11}H_{12}$, 144,0934); nmr (CCl_4) δ 0.93 (t, 3 H, $-CH_3$), 1.8 (m, 4 H, $-CH_2CH_2-$), 7.26 (m, 5 H, Ph), −125.0 (m, $PhCF_2-$), −127.8 (m, $-CF_2C_3H_7$).

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Registry No.—**1a,** 501-65-5; **1b,** 673-32-5; **1c,** 4250-81-1; **2a,** 425-32-1; **2b,** 14210-87-8; **2c,** 51821-09-1; XeF_2, 13709-36-9.