J. Org. Chem. 1985, 50, 499–502

performed on a PDP 11/34 computer with a GT 42 graphics terminal and a Printronix lineprinter/plotter at the Computer Graphics Laboratory for Organic Chemistry of the University of Lund.

Kinetics. Competitive epoxidation was carried out as follows. Equal amounts (ca. 0.08 mmol) of each of two olefins were dissolved in 5 mL of methylene chloride at 20 °C and supplied with $^1/_{20}$ equivalent of *m*-chloroperbenzoic acid. The mixture was stirred for ca. 1 h and analyzed directly on a 1.5 m × 3 mm 3% OV 101 on Chromosorb Q column with a Varian 1400 gas chromatograph equipped with an electronic integrator (Hewlett Packard 3390 A). The relative rates were determined from the relative amounts of the corresponding epoxides produced, after correction for response factors. The epoxides have the following characteristics.

1,2-Epoxyoctane: ^{1}H NMR ($CDCl_3$) δ 0.89 (t, 3 H, $J = 6.65$ Hz), 2.46 (d of d, 1 H, $^2J = 4.6$ Hz, $^3J = 2.7$ Hz), 2.74 (d of d, 1 H, $^2J = 4.6$ Hz, $^3J = 4.6$ Hz), 2.90 (m, 1 H); mass spectrum, *m/e* (relative intensity) 128 (3), 85 (15), 81 (20), 71 (100), 58 (73), 55 (93), 45 (19). **3,4-Diethyl-3,4-epoxyhexane**: ^{1}H NMR ($CDCl_3$) δ 0.89 (t, 4 × 3 H, $J = 7.40$ Hz), 1.37 (quartet of d, 4 × 1 H, $^{AB}J = 14.4$ Hz, $^3J = 7.40$ Hz); mass spectrum, *m/e* (relative intensity) 156 (1), 86 (39), 69 (10), 57 (100), 45 (37). **4,5-Dipropyl-4,5-epoxyoctane**: ^{1}H NMR ($CDCl_3$) δ 0.93 (t, 4 × 3 H, $J = 7.04$ Hz), 1.34–1.63 (m, 4 × 4 H); mass spectrum, *m/e* (relative intensity) 213 (3), 114 (32), 99 (26), 86 (38), 71 (100), 55 (70). **4,5-Bis(2-methylpropyl)-2,7-dimethyl-4,5-epoxyoctane**: ^{1}H NMR ($CDCl_3$) δ 0.86 (d, 4 × 3 H, $J = 6.40$ Hz), 0.90 (d, 4 × 3 H, $J = 6.40$ Hz), 1.45 (m, 4 × 2 H), 1.74 (m, 4 × 1 H); mass spectrum, *m/e* (relative intensity) 269 (2), 142 (24), 127 (48), 100 (21), 85 (90), 69 (56), 57 (100). **2,3-Dibenzyl-1,4-diphenyl-2,3-epoxybutane**: ^{1}H NMR ($CDCl_3$) δ 3.08 (q, 4 × 2 H, $J = 14.72$ Hz), 7.20–7.35 (m, 4 × 5 H); mass spectrum, *m/e* (relative intensity) 313 (5), 91 (100).

Molecular mechanics calculations were performed by using the MM2 (MMP2) program developed by Allinger and co-workers employing their 1977 force field.[13]

Crystallography. Crystals suitable for X-ray analysis of **5** were obtained by slow crystallization from heptane.

Crystal data: $C_{30}H_{28}$, $M_r = 388.56$, monoclinic, space group $C2/c$, $a = 26.05$ (1) Å, $b = 13.450$ (7) Å, $c = 21.360$ (7) Å, $\beta = 113.18$ (4)°, $U = 6913$ (5) Å^3, $Z = 12$, $Dc = 1.13$ Mg m^{-3}, μ(Mo K_α) = 0.7 cm^{-1}. 1922 reflections with $I > 3\,\sigma(I)$, final R value = 0.065, $R_W = 0.058$. The structure was solved with MULTAN 80 which revealed the positions of all non-hydrogen atoms. The atomic positions for the hydrogen atoms were found after least-squares refinement and difference Fourier analysis. The final refinement cycle included anisotropic temperature factors for the non-hydrogen atoms and isotropic temperature factors for the hydrogen atoms. $F_o - F_c$ tables can be obtained from L. Anderson at Chalmers University of Technology, Göteborg.

Acknowledgment. We thank Professor O. Lindqvist, CTH, Göteborg for putting the facilities for the X-ray analysis at our disposal, and Dr. T. Liljefors and Professor J. Sandström for valuable discussions and advice. Grants from the Swedish Natural Science Research Council and the Knut and Alice Wallenberg Foundation, covering the cost of the Nicolet 360-MHz NMR spectrometer, are gratefully acknowledged.

Supplementary Material Available: Figures showing the gas-phase ^{1}H NMR spectrum of compound **4** (Figure S1), a Pluto plot of the ground-state conformation of compound **3** (Figure S2), and a stereoview of the X-ray structure of compound **5** (Figure S3) and X-ray crystallographic data (39 pages). Ordering information is given on any current masthead page.

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The Reaction of Organic Molecules on Solid Surfaces. 2. An Efficient Method for the Preparation of Deuterated Alumina

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The construction and use of a simple and inexpensive device for the deuteration of alumina is described. Two methods are present for analyzing the extent of deuterating the solid: ^{1}H NMR analysis of the water of dehydration and ^{1}H NMR analysis of the phenylacetylene equilibrated with the solid. A theory is presented which should prove helpful in finding the optimum conditions for the preparation of the solid catalyst. When phenylacetylene is used as a model substrate, chromatographic and slurry methods for the deuteration of acidic organic molecules are compared.

Alumina (Al_2O_3) is an appropriate medium on which to replace the acidic hydrogens of suitable substrates with deuterium or tritium because of the basic nature of alumina.[1] In order to prepare deuterated alumina, it is first necessary to drive off the hydrogen as H_2O and then replace it with D_2O. Unfortunately, it is not possible to remove all the hydrogen by simply heating alumina.[2] However, repetition of the heating plus addition of D_2O procedure (cycle) will ultimately yield the desired result.[3-5] We have constructed a simple-to-use and inexpensive device for the efficient deuteration of alumina which incorporates elements of the previous procedures.[3-5] We wish to report on these efforts as well as on methods for testing and using the alumina effectively.

Description and Operation of Deuteration Apparatus. The device we have constructed (Figure 1) is similar to those described by Mislow[3] and Kopecky[4] except that the flask is demountable so that the solid can be shaken (under vacuum) at appropriate times, a frit (d) is inserted to prevent the alumina from being pulled into the vacuum pump, and most importantly, a stopcock (e) is

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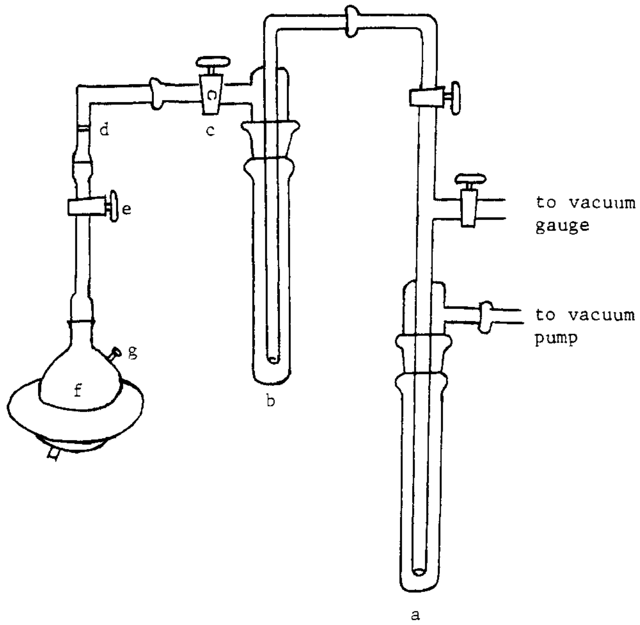

Figure 1. A diagram of the vacuum apparatus used for the dehydration and H_2O–D_2O exchange on alumina.

inserted above the alumina-containing flask to aid in equilibrating the H and D (vide infra). The system makes use of a vacuum apparatus requiring two traps (a and b), both of which are cooled in liquid nitrogen. Trap b is used to collect the water removed from the alumina which can then be analyzed for deuterium content by ^1H NMR or mass spectrometry. Trap a is used to protect the vacuum pump from water contamination. To trap b is connected a three way stopcock (c) which permits the release of the vacuum as necessary. The system is also equipped with a glass frit (d), which has already been described. To this is attached a removable joint containing a two way stopcock (e) which isolates the round-bottom flask (f) when adding the D_2O. The D_2O is introduced via syringe through a rubber septum (g) which was found to hold up quite well to the high vacuum and temperatures used. The temperature of the alumina was measured by a thermocouple placed between the round-bottom flask and the heating mantle. The apparatus was never run above 450 °C because higher temperatures softened the round bottom flask, causing the flask to be pulled inward under vacuum.

The replacement of H by D on the alumina is carried out by placing the alumina in the round-bottom flask which is connected to the vacuum system and the entire system is evacuated to 0.005 mmHg. The round-bottom flask containing the alumina is then heated to the appropriate temperature and the water vapor evolved is collected in trap (b). After a given period of time the heating mantle is removed and the dehydrated alumina allowed to cool. The round-bottom flask is then closed off from the vacuum using stopcock e, and D_2O (normally 6 wt % based on the original weight of alumina) is injected; this reaction is extremely exothermic. (If desired, the round bottom flask can be removed under vacuum at this stage and shaken.) To insure complete mixing of H and D, the evacuated flask is now heated to 350 °C for 6 h with stopcock e closed to the vacuum pump.[6] Thus, water (H_2O, HDO, and D_2O) in the vapor will equilibrate with corresponding species on the solid and the H and D will not only mix on the solid but also the vapor.[6] The alumina is then allowed to cool and the flask reopened to vacuum and dehydrated as before.

Table I. Percent of Deuterium on Surface as a Function of Cycle Number

cycle no.	% D_2O in collected water	% deuteration of phenylacetylene[a]
1	76.9	83.5
2	89.4	92.1
3	95.0	95.0
4	98.0	97.0
5	99.0	99.0
6	99.6	

[a] Reactions were carried out by mixing 0.1 mL of $C_6H_5C{\equiv}CH$ with 10 g of deuterated aluminia in 20 mL of pentane for 16–18 h. There is at least a 60:1 ratio of D on the alumina to exchangeable H on the phenylacetylene.

Two simple methods of analysis have been used to determine the relative amounts of hydrogen and deuterium on the surface. First, we have analyzed the trapped water by ^1H NMR with tetramethylammonium bromide as an internal standard. Typical results as a function of cycle number are shown in Table I. As one would expect, the amount of D_2O in the water increases as the cycle number goes up.

The second method of analysis involves deuterating phenylacetylene in pentane with a sample of the alumina (slurry method). The phenylacetylene is then analyzed for deuterium content by ^1H NMR after equilibrium has been attained.[5] Typical results as a function of cycle number are shown in Table I. Note that the phenylacetylene experiments were run on the same alumina used for the water analyses.

$$\underset{1}{\mathrm{PhC{\equiv}CH}} \xrightarrow{D_2O/Al_2O_3} \underset{1\text{-}d}{\mathrm{PhC{\equiv}CD}}$$

As can be seen (Table I), the two distinctly different methods of analysis give comparable results. It is clear that 3–4 cycles are needed to obtain an acceptable deuterated alumina for exchange reactions.

Theoretical Analysis of Cycling Procedure. In calculating the efficiency of the deuteration process, there are three quantities that must be taken into account: mmoles of H initially on the solid (not necessarily known), mmoles of H and D removed as water per dehydration cycle (temperature dependent), and the amount of D_2O added per cycle. Under assumptions described in the Experimental Section, the following equation can be derived:

$$\% \mathrm{D} = \left[\frac{m_\mathrm{D} \sum_{n=0}^{n=a-1} (1-f)^n}{m_\mathrm{D} \sum_{n=0}^{n=a-1} (1-f)^n + m_\mathrm{H}(1-f)^a} \right] 100$$

Here % D represents the percentage of D on the surface after a cycles, m_H represents the mmoles of H initially on the surface and m_D the mmoles of D added (as D_2O) per cycle; f represents the fraction of D and H removed per cycle and $1 - f$ then is the amount of each which remains on the surface. Normally an exact solution of the equation will not yield an integer value for a; experimentally, of course, it must be a whole number. Thus the values reported in Tables II and III represent the first whole number above the exact solution.

Table II summarizes the conditions required to attain 98% D under several values of f, the amount of H and D removed per cycle, and m_D; Table III records the results required to attain 99.5% D. Not surprisingly, as f goes up,

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[6] This approach to mixing of the isotopes follows from the elegant studies of Haldeman and Emmett. Haldeman, R. G.; Emmett, P. H. *J. Am. Chem. Soc.* **1956**, *78*, 2917.

Table II. Number of Cycles Required To Attain 98% D[a]

	amt of D_2O added/cycle		
f	300 mg (3%)	600 mg (6%)	900 mg (9%)
0.25	12	10	9
0.50	6	5	5
0.75	4	3	3
0.90	2	2	2
0.99	2[b]	1	1

[a] A 10-g sample of alumina is assumed to have m_H = 200/3 mmol (600 mg of H_2O). [b] Slightly above 1.

Table III. Number of Cycles Required To Attain 99.5% D[a]

	amt of D_2O added/cycle		
f	300 mg (3%)	600 mg (6%)	900 mg (9%)
0.25	17	14	13
0.50	8	7	7
0.75	5	4	4
0.90	3	3	3
0.99	2	2	2

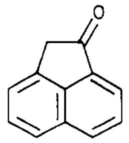
[a] A 10-g sample of alumina is assumed to have m_H = 200/3 mmol (600 mg of H_2O).

the number of cycles required to get the desired result goes down. Because *f* can be regulated, at least to some extent by temperature,[2] the dehydration temperature should be kept as high as possible. Quite unexpected, however, was the observation that there is little to be gained in using large amounts of D_2O: addition of 3% of D_2O is almost as effective as addition of 6% D_2O; 6%, in turn, isn't much less effective than 9%.

Behavior of Phenylacetylene on the Deuterated Solid. We wish to describe several experiments that other researchers might find helpful when performing the exchange reactions. We used phenylacetylene as the model substrate because of the ease of handling and our experience in dealing with it.[5] We compared two procedures of exchange: (1) chromatography of the substrate through a column of deuterated alumina and (2) stirring a solution of the substrate in the presence of the solid reagent (slurry method).

Of the two methods, chromatography should be superior because the substrate is continually exposed to fresh deuterated alumina. We have in fact attained 100% D by passing 100-mg samples of phenylacetylene (**1**) and acenaphthenone (**2**) through 10-g columns of high quality reagent. The slurry method can never attain 100% D because the substrate is always exposed to the total pool of D and H. One can approach 100%, however, by keeping the ratio of D on the surface to H on the substrate high.

The chromatography procedure is particularly well suited to substrates that undergo the exchange reaction at rates comparable or faster than the rate at which it is eluted through the column. Chromatography is not a good choice, however, for substrates such as camphor (**3**) which undergo exchange at a very slow rate.[5]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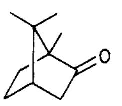
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It is also difficult to pack columns in a consistent and reproducible manner. We have often observed variable % D's, although the conditions were reproduced as accurately as possible. Furthermore, even under the best of circumstances, there is a limit to the amount of substrate which can be efficiently passed through a column; there is also a limit to the number of times a column can be reused. To explore these limits, we have repeatedly passed fresh 100-mg samples of phenylacetylene through a 10-g column of deuterated alumina containing approximately 50 mmol of D; the phenylacetylene samples were analyzed by ^1H NMR for deuterium content. A plot of % D vs. total grams of phenylacetylene passed through the column (Figure 2) is essentially linear with 100% D being realized for the first sample and greater than 25% D after 3.4 g of phenylacetylene had been eluted from the column. Extrapolation of the curve to 0% D suggests that greater than 4.4 g of phenylacetylene can be passed through the column before 0% deuterium incorporation is observed. Thus 4.4 g of the hydrocarbon had an average deuterium content of 50% D. If one were to increase the amount of alumina by 3- or 4-fold, 4.4 g of substrate would elute from the column with close to 100% D. One can conclude from this analysis that large quantities of substrate can be deuterated by the chromatography method if an appropriate amount of alumina is used.

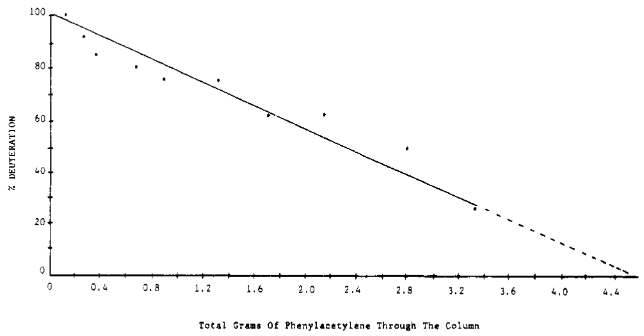

Figure 2. Percent deuteration vs. total grams of phenylacetylene through the column.

Table IV. Deuteration of Phenylacetylene by the Slurry Method as a Function of Solvent[a]

solvent	equilibrium % D
cyclohexane	84
ligroin (30–60 °C)	84
carbon tetrachloride	84
pentane	83
methylene chloride	82
diethyl ether	80
tetrahydrofuran	83

[a] Reactions were carried out on 0.1 mL of phenylacetylene in 20 mL of solvent with 10 g of alumina (containing approximately 85% D).

The slurry method, i.e., stirring a solution of the substrate (usually in pentane) with the deuterated alumina, also has advantages. The procedure is simple and is ideal for substrates that are deuterated at a slow rate. As noted previously, it is not possible to obtain 100% D with a single exposure (pass) of the substrate to the solid. Not surprisingly, we have found that by using multiple passes and increasing the ratio of D to H, percentages approaching 100% D can be attained.

Finally, we wish to note that solvent is not an important variable. As can be seen in Table IV essentially the same equilibrium value is obtained in all cases.

Experimental Section

^1H NMR spectra were recorded on JOEL F XQ 90-MHz and Nicolet 200-MHz spectrometers with deuteriochloroform as solvent and tetramethylsilane as internal standard. Mass spectra were recorded on a Hewlett Packard GC mass spectrometer with HP 3954 data system.

The alumina used was Brockman neutral alumina (activity I, 80–200 mesh) available from the Fischer Chemical Company.

Solvents were reagent grade and most were used as received. Pentane was distilled and stored over molecular sieves. Tetrahydrofuran was distilled under nitrogen from lithium aluminum hydride.

Deuteration Apparatus. The design is shown in Figure 1 and its use described in the text.

Hydrogen–Deuterium Analysis of Water. For the sake of the analysis, the sample is assumed to contain only H_2O and D_2O. To a given weight of water is added a known weight of $(CH_3)_4N^+Br^-$ (I) and the relative areas of the hydrogen in water to hydrogen in I determined by ^{1}H NMR. From this the following equations are derived:

$$\text{mole}_{H_2O} \times M_{r_{H_2O}} + \text{mole}_{D_2O} \times M_{r_{D_2O}} = \text{weight of water}$$

$$\text{area}_{\text{water}} \propto 2\ \text{mole}_{H_2O} \qquad \text{area}_{I} \propto 12\ \text{mole}_{I}$$

$$\frac{\text{area}_{\text{water}}}{\text{area}_{I}} = \frac{2\ \text{mole}_{H_2O}}{12\ \text{mole}_{I}}$$

$$\text{mole}_{I} = \frac{\text{weight of I}}{M_{r_I}}$$

From these equations mole_{H_2O} and mole_{D_2O} are easily determined. Control experiments demonstrated that pure H_2O gives the correct integration for a given weight of $(CH_3)_4N^+Br^-$. Control experiments also demonstrate that relaxation phenomena do not affect the integration of the water peak (H_2O and HDO could have different relaxation rates).

Hydrogen–Deuterium Analysis of Phenylacetylene. The acetylene % D was determined by ^{1}H NMR. If one assumes that the aromatic sites remain undeuterated, the following equations are true:

$$\text{area}_{Ar} \propto 5\ \text{mole}_{C_6H_5C\equiv CH} + 5\ \text{mole}_{C_6H_5C\equiv CD}$$

$$\text{area}_{Ac} \propto 1\ \text{mole}_{C_6H_5C\equiv CH}$$

$$\frac{\text{area}_{Ar}}{\text{area}_{Ac}} = 5 + 5\,\frac{\text{mole}_{C_6H_5C\equiv CD}}{\text{mole}_{C_6H_5C\equiv CH}}$$

where Ar = aromatic sites and Ac = acetylenic site. From the last equation the relative amounts of deuterated and nondeuterated phenylacetylene can be determined and from which the % D is calculated. Occasionally the NMR results were compared with those obtained by mass spectrometry. The two methods gave identical results.

Surface Area Determination. The surface area of the Brockman alumina was determined by the method of Hoffmann et al.[7] (originally used for silica gel) and found to be close to 300 m^2/g.[8]

Procedures for Deuteration of Phenylacetylene. A. Chromatography Method. A burette is slurry packed in pentane with 10 g of alumina and the phenylacetylene adsorbed at the top. After passing a suitable amount of pentane through the column to remove the acetylene, most of the solvent is carefully removed in vacuo and the phenylacetylene analyzed for deuterium content by ^{1}H NMR.

B. Slurry Method. In a round-bottom or Erlenmeyer flask containing a teflon coated stirring bar is placed a solution of phenylacetylene (commonly 0.1 mL in 20 mL of pentane) and alumina (commonly 10 g). The mixture is stirred and, after an appropriate period of time, the solid is separated from the solution which is worked up and analyzed as described above.

Derivation of the Mathematical Equation Describing the Cycling Procedure. We are given a certain weight of alumina which containse m_H moles of hydrogen. We now dehydrate the solid and remove a fraction f of hydrogen as H_2O. If m_H' are the moles of H left on the solid, $m_H' = (1 - f)m_H$. Let us now add m_D moles of deuterium as D_2O ($m_D = 2m_{D_2O}$). The % D for cycle one alumina is now given by

$$\%\ D = \left[\frac{m_D}{m_D + m_H'}\right]100$$

Let us now dehydrate again under identical conditions such that the same fraction f of H and D is removed as before. It now follows that H on the surface = $m_H'(1 - f)$ and D on the surface = $m_D(1 - f)$. Again if we add m_D moles of D the % D for cycle two alumina is

$$\%\ D = \left[\frac{m_D + m_D(1-f)}{m_D + m_D(1-f) + m_H'(1-f)}\right]100$$

It follows that for cycle three alumina

$$\%\ D = \left[\frac{m_D + m_D(1-f) + m_D(1-f)^2}{m_D + m_D(1-f) + m_D(1-f)^2 + m_H'(1-f)^2}\right]100 = \left[\frac{m_D \sum\limits_{n=0}^{n=2}(1-f)^n}{m_D \sum\limits_{n=0}^{n=2}(1-f)^n + m_H'(1-f)^2}\right]100$$

Generalizing one obtains for cycle a alumina

$$\%\ D = \left[\frac{m_D \sum\limits_{n=0}^{n=a-1}(1-f)^n}{m_D \sum\limits_{n=0}^{n=a-1}(1-f)^n + m_H'(1-f)^{a-1}}\right]100$$

But $m_H' = m_H(1 - f)$, thus

$$\%\ D = \left[\frac{m_D \sum\limits_{n=0}^{n=a-1}(1-f)^n}{m_D \sum\limits_{n=0}^{n=a-1}(1-f)^n + m_H(1-f)^{a}}\right]100$$

Acknowledgment. We wish to thank the National Science Foundation for funds to purchase the Nicolet 200-MHz NMR spectrometer and for partial support of this work.

Registry No. Al_2O_3, 1344-28-1; phenylacetylene, 536-74-3; hydrogen, 1333-74-0; deuterium, 7782-39-0.

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