rowing further suggests that an attractive interaction exists between the phosphine side arms and the fullerene.

In summary, this work shows that the guest/host nature of fullerene/phenyl interactions can be chemically manipulated to produce novel solid-state aggregates. The phenyl-X-Y-phenyl unit (X, Y are first row atoms) has the proper geometry to chelate a portion of C_{60}.

Acknowledgment. We thank the National Science Foundation (CHE 9022909) for support and Johnson-Matthey, Inc. for a loan of iridium chloride.

Supplementary Material Available: Tables of atomic coordinates, bond distances, bond angles, anisotropic thermal parameters, and hydrogen atom positions for **2** (10 pages); listings of observed and calculated structure factors for **2** (16 pages). Ordering information is given on any current masthead page.

Hole Transfer Promoted Hydrogenation: One-Electron Oxidation as a Strategy for the Selective Reduction of π Bonds

Gholam A. Mirafzal and Nathan L. Bauld*

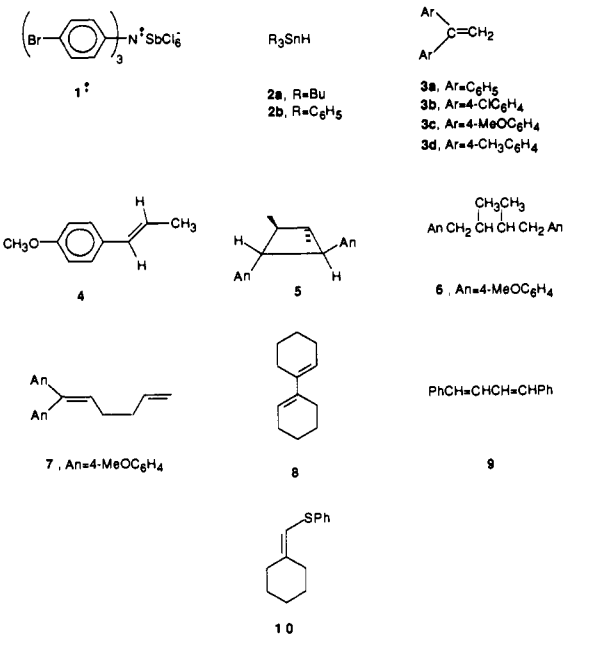
Department of Chemistry and Biochemistry
The University of Texas at Austin
Austin, Texas 78712

Received March 23, 1992

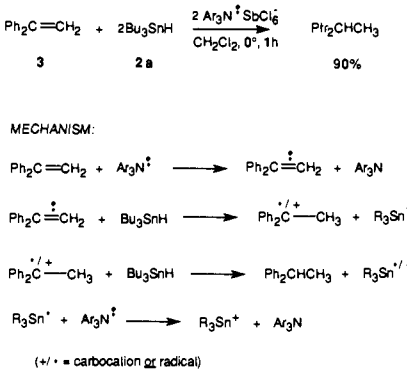
One-electron oxidation (hole formation) is increasingly being exploited as a fundamental option for activating molecules toward synthetically useful chemistry mediated by cation radicals.[1-5] In the context of multifunctional molecules, reactivity can be specifically directed to the most oxidizable functionality through the use of mild hole-transfer agents such as tris(4-bromophenyl)-aminium hexachloroantimonate ($\mathbf{1}^{\bullet+}$) (Chart I). This strategy has recently been used to develop an efficient epoxidation procedure in which selectivity is based solely upon, and is highly sensitive to, relative oxidizability.[6] The present communication describes a similarly selective method for the dihydrogenation of relatively oxidizable ($E_{ox} \leq 1.5$ V) functionalities, including conjugated dienes, styrenes, electron-rich alkenes, aromatics, and even strained σ bonds.

The reduction of an alkene cation radical to an alkane formally requires the transfer of one hydrogen atom and one hydride ion to the cation radical. The hydrogen-transfer agents found most effective in this work were tributyltin hydride (**2a**) and triphenyltin hydride (**2b**). The concept of promoting alkene reduction by initial one-electron oxidation is illustrated by the reduction of 1,1-diphenylethene (**3a**, E_{ox} = 1.22 V, Scheme I, 90% yield). The important mechanistic issue of the sequence of hydrogen atom and hydride transfer, i.e., whether the initial product of hydrogen transfer is a carbocation or a free radical, has not yet been resolved but is currently under investigation. The ability of $\mathbf{1}^{\bullet+}$ to ionize **3a** under the present reaction conditions has previously been established, and the generation of $\mathbf{3a}^{\bullet+}$ is further confirmed by the observation of minor amounts of the cyclodimer of **3a** in the product.[6] A major substituent effect appropriate to the ionization of **3a** is suggested by the complete unreactivity of the corresponding *p,p'*-dichloro derivative (**3b**) during a reaction time of 1 h. In contrast to both **3a** and **3b**, the *p,p'*-dimethoxy derivative (**3c**) was completely reduced within 1 min (93%). A quantitative study

Chart I



Scheme I



of the competitive reduction of **3a** and its corresponding 4,4'-dimethyl derivative (**3d**) revealed a relative reaction rate of 1:167, corresponding to a ρ value of ca. −7.2 (using σ_p^+) or −3.6 (using $\sum\sigma_p^+$). A ρ value of −4.0 per aryl ring has been found to correspond to full carbocation formation in the equilibrium protonation of 1,1-diarylethenes.[7] The possibility of a Bronsted acid catalyzed mechanism is ruled out by the observation that excess 2,6-di-*tert*-butylpyridine fails to suppress the reaction.[1,2,8] Moreover, the reduction of 2,4-dimethyl-1,3-pentadiene yields, as a byproduct, the cyclodimer resulting from hole transfer catalyzed Diels-Alder cycloaddition but none of the acid-catalyzed cyclodimerization product.[1,2] Similarly, the hydrogenations of 1,3-cyclohexadiene and 1,1'-bicyclohexenyl also yield the well-known hole transfer catalyzed cyclodimers as byproducts.[1,2]

In the case of *trans*-anethole (**4**), hole transfer catalyzed cyclodimerization strongly predominates, affording the cyclobutadimer (**5**).[9] However, **5** is also readily oxidizable, and the proposed long bond[9,10] of $\mathbf{5}^{\bullet+}$ is then reductively cleaved to afford **6** (80%). The dihydrogenation of **4** was achieved, nevertheless, by using the more reactive triphenyltin hydride (**2b**) as the reductant (55%). The selectivity of hole transfer promoted hydrogenation is illustrated by the reduction of **7**, which occurs exclusively at the more ionizable double bond (95% yield). Simple double bonds such as those in norbornene and 1-octene are not

(1) Bauld, N. L. *Tetrahedron* **1989**, *45* (17), 5307-5363.
(2) Bauld, N. L. *Advances in Electron Transfer Chemistry*; Mariano, P. S., Ed.; JAI Press: Greenwich, CT, 1992; Vol. 2.
(3) Todd, W. P.; Dinnocenzo, J. P.; Farid, S.; Goodman, J. L.; Gould, I. R. *J. Am. Chem. Soc.* **1991**, *113*, 3601-3602.
(4) Gieseler, A.; Steckhan, E.; Wiest, O.; Knoch, F. *J. Org. Chem.* **1991**, *56*, 1405.
(5) Mattay, J.; Vondenhof, M. *Top. Curr. Chem.* **1991**, *159*, 219-255.
(6) Bauld, N. L.; Mirafzal, G. A. *J. Am. Chem. Soc.* **1991**, *113*, 3613-3614.
(7) Deno, N. C.; Groves, P. T.; Saines, G. *J. Am. Chem. Soc.* **1959**, *81*, 5790-5795.
(8) Gassman, P. G.; Singleton, D. A. *J. Am. Chem. Soc.* **1984**, *106*, 7993.
(9) Bauld, N. L.; Pabon, R. *J. Am. Chem. Soc.* **1983**, *105*, 633-634.
(10) Pabon, R. A.; Bauld, N. L. *J. Am. Chem. Soc.* **1984**, *106*, 1145-1146.

0002-7863/92/1514-5457$03.00/0

amenable to reduction via this method.

The reduction of conjugated dienes is illustrated with **8** and **9**. The sole product of the reduction of **8** is cyclohexenylidenecyclohexane (90%), corresponding to exclusive 1,4-dihydrogenation. However, **9** yields *trans*-1,4-diphenyl-2-butene and *trans*-1,4-diphenyl-1-butene in the ratio 2:1 (75%).

A very attractive ancillary feature of hole transfer promoted hydrogenation is the absence of hydrogenolysis, even of carbon–sulfur bonds. The reduction of **10** is efficient (88%), and the retention of the phenylthio function clearly contrasts with catalytic hydrogenation. Reduction of suitably ionizable aromatics is also feasible. Anthracene affords 9,10-dihydroanthracene (70%), but less ionizable substrates (phenanthrene, naphthalene) are inert.

Hole transfer promoted hydrogenation is experimentally convenient,[11] and the required reagents (**1**$^{\bullet+}$, **2a,b**) are readily available. The unique and superior selectivity characteristics of the reaction suggest potential synthetic utility. Mechanistically, the intervention of cation radical intermediates is strongly supported, but the likely subsequent involvement of carbocations and/or radicals remains to be established.

Acknowledgment. The authors thank the National Science Foundation (NSF CHE 8822051) for support of this research.

Supplementary Material Available: Listings of experimental details and characterization data for the olefin hydrogenations mentioned in the text (6 pages). Ordering information is given on any current masthead page.

(11) The appropriate substrate is dissolved in dichloromethane solution (~0.15 M) and cooled to 0 °C. The hydride reagent (220 mol %) is then added, followed by **1**$^{\bullet+}$ (200 mol %). Both reagents are available from the Aldrich Chemical Company. The reaction mixture is stirred for 1 min to 1 h, depending upon the substrate (**3a** requires 1 h, anthracene ca. 0.5 h, and all other substrates in this study 1–2 min). The reactions are quenched with excess K_2CO_3/CH_3OH. Products are purified by ether/brine extraction followed by flash silica gel chromatography (hexane followed by 8:2 hexane/ethyl acetate).

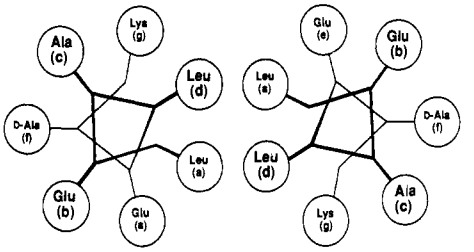
The Helix-Forming Propensity of D-Alanine in a Right-Handed α-Helix

Robert Fairman, Spencer J. Anthony-Cahill, and William F. DeGrado*

The Du Pont Merck Pharmaceutical Company
Experimental Station, P.O. Box 80328
Wilmington, Delaware 19880-0328

Received March 4, 1992

The design of peptides and proteins requires an understanding of the features that stabilize protein secondary, tertiary, and quaternary structures.[1] Toward this goal we have developed a model, two-stranded, coiled-coil peptide that allows one to determine the contributions of individual amino acids to the stability of α-helices[2] (Figure 1). This peptide adopts a random coil as a monomer in dilute aqueous solution, but forms α-helical dimers in more concentrated solution. The free energy of dimerization, $\Delta G°_{dim}$, can be determined by measuring the concentration dependence of α-helix formation as monitored by circular dichroism (CD). Systematic changes on the solvent-exposed face of the helices are then made and the resulting changes in $\Delta G°_{dim}$ measured. These changes can be interpreted in terms of their effect on α-helix formation, an obligatory step in dimerization.[2]



Ac-EWEALEKKLAALE-(D-Ala)-KLQALEKKLEALEHG-$\overset{O}{\overset{\|}{C}}$-NH$_2$

Figure 1. Helical wheel representation of the heptapeptide repeating unit used in the design of the helical pair. The sequence of the model peptide is shown at the bottom.

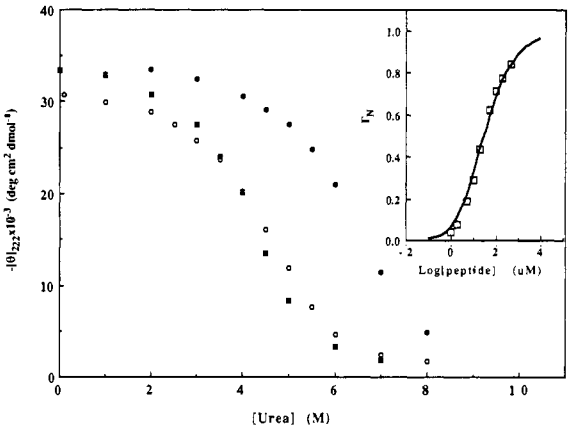


Figure 2. Urea denaturations of the L-Ala peptide (●), Gly peptide (■), and D-Ala peptide (○). $[\theta]_{222}$ was measured as described previously.[2] The helical contents of the peptides in the absence of urea are the same within experimental error (−34 000 ± 2000 deg cm^2 dmol^{-1}) Inset: Peptide concentration dependence[2] for the D-Ala peptide as measured by CD. F_N represents the fraction of coiled coil dimer as calculated from $[\theta]_{222}$. The fitted curve, describing a simple monomer–dimer equilibrium, was generated using MLAB (Civilised Software, Inc., Bethesda, MD).

In this paper, we investigate the effect of substituting D-Ala into our model system. Although D amino acids are used widely in peptides, their effect on the free energy of forming a right-handed α-helix has been unknown.

The model peptide described previously[2] was prepared with D-Ala in the guest site. In aqueous solution, the peptide has a CD spectrum with minima at 208 and 222 nm and a maximum at 192 nm, predictive of a right-handed α-helix. Figure 2 illustrates $[\theta]_{222}$ (a measure of the handedness and extent of α-helix formation) versus [urea] for peptides with Gly, L-Ala, and D-Ala at the guest position. Similar to Gly, D-Ala is destabilizing relative to L-Ala. $\Delta G°_{dim}$ was obtained from the concentration dependence of $[\theta]_{222}$ (Figure 2, inset), and $\Delta\Delta G°$ was found to be unfavorable by 0.95 kcal/mol for D-Ala as compared to 0.77 kcal/mol for Gly, with L-Ala as the standard.

Several features probably account for the destabilizing effect of D-Ala relative to L-Ala. The backbone angles available to D-Ala in the right-handed α-helical portion of the ϕ, ψ map are more restricted and of higher energy than for L-Ala. Also, there are unfavorable steric interactions between the C_β of D-Ala at position i and the carbonyl oxygen atoms from residues i and $i-1$ in a right-handed α-helix.[3]

Hermans and co-workers[3] have recently determined similar values for $\Delta\Delta G°$ between Gly, L-Ala, and D-Ala using perturbational molecular dynamics ($\Delta\Delta G°$ values for Gly and D-Ala are 1.1 and 1.2 kcal/mol, respectively, with L-Ala as the standard state). These theoretical values are in good agreement with our experimental results, given the large differences in the two methods.

* Author to whom correspondence should be addressed.

(1) DeGrado, W. F.; Wasserman, Z. R.; Lear, J. D. *Science* **1989**, *243*, 622–628.

(2) O'Neil, K. T.; DeGrado, W. F. *Science* **1990**, *250*, 646–651. The peptides used in the current study, Ac-EWEALEKKLAALE-(Xxx)-KLQALEKKLEALEHG-CONH$_2$ (Xxx = D-Ala, L-Ala, or Gly), were prepared as described in the original publication or by a modification of this procedure.

(3) Hermans, J.; Anderson, A. G.; Yun, R. H. *Biochemistry*, in press.

0002-7863/92/1514-5458$03.00/0