$CO_2Me{\cdot}Li{\cdot}K^+$, 105183-50-4; (*S,S*)-$\overline{CH_2OC(Me)_2OCHCH_2CH(OH)CH_2C(OMe)}$=$NC^-(CHO)CO_2Me{\cdot}Li{\cdot}K^+$, 105183-51-5; 4-$ClC_1H_4CHO$, 104-88-1; PhCHO, 100-52-7; Me_2CHCHO, 78-84-2; $PhCH_2Br$, 100-39-0; $(EtO)_2P(O)CH_2CH$=NBu-*t*, 29940-81-6; mesitaldehyde dimethyl acetal, 64761-29-1; (*S*)-diethyl malate, 691-84-9; (L)-malic acid, 97-67-6; (*S*)-diethyl malate 2-(1-methyl-1-methoxyethyl) ether, 66348-32-1; 2-methoxypropene, 116-11-0; (*S*)-1,2,4-butanetriol 2-(1-methyl-1-methoxyethyl) ether, 66348-33-2; (±)-1,2,4-butanetriol, 6810-31-7; methyl α-[(methoxyethylidene)amino]acetate, 64991-38-4; vinyltributylphosphonium bromide, 1883-19-8; methyl acetimidate hydrochloride, 14777-27-6; methyl glycinate hydrochloride, 5680-79-5.

$(\eta^5\text{-}C_5H_5)Fe(CO)_2(\eta^1\text{-}C_5H_5)$. A Useful Synthetic Equivalent of 5-Amino-1,3-cyclopentadiene in Cycloaddition Reactions[1]

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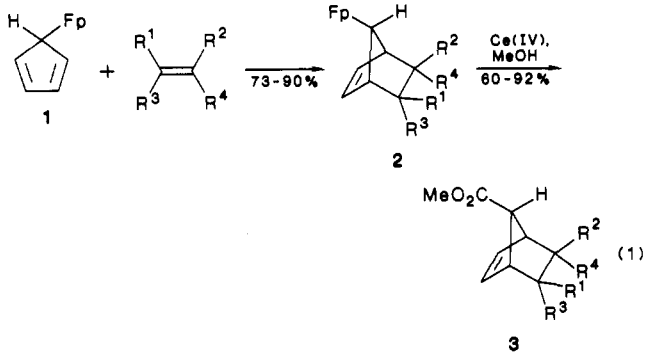
Diels–Alder reactions of 5-amino-1,3-cyclopentadiene have not been reported, and other stereoselective, high-yield routes to substituted bicyclo[2.2.1]hept-2-en-7-*syn*-amines are limited. This paper reports use of $(\eta^5\text{-}C_5H_5)Fe(CO)_2(\eta^1\text{-}C_5H_5)$ (**1**) as a synthetic equivalent of 5-amino-1,3-cyclopentadiene in cycloaddition reactions. The previously reported cycloadducts of **1** and alkenes were treated with ammonium cerium(IV) nitrate, bromine, or chlorine in acetonitrile containing sodium azide to give the corresponding acyl azides in which the CON_3 group replaced the $(\eta^5\text{-}C_5H_5)Fe(CO)_2$ group with retention of stereochemistry in good yield. Thermal Curtius rearrangement of these acyl azides proceeded stereospecifically in excellent yield. This regioselective and stereoselective sequence provides a useful route to substituted 7-*syn*-amino-2-norbornenes.

Recently, the reaction of $Fp(\eta^1\text{-}C_5H_5)$ (**1**), where Fp = $(\eta^5\text{-}C_5H_5)Fe(CO)_2$, with a variety of unsaturated compounds to give cycloadducts in good yield was reported.[2,3] These reactions all occur regio- and stereoselectively to afford 7-*syn*-Fp cycloadducts **2**, as shown in eq 1. Furthermore, stereospecific replacement of the Fp moiety in these cycloadducts by a CO_2Me group with retention of configuration to give **3** was found to occur in good yield by oxidation with ammonium cerium(IV) nitrate in methanol saturated with carbon monoxide.[2,3] This two-step sequence, cycloaddition followed by oxidation, renders $Fp(\eta^1\text{-}C_5H_5)$ a synthetic equivalent of methyl 1,3-cyclopentadiene-5-carboxylate in cycloaddition reactions.



The utility of this synthetic methodology would be enhanced if the Fp moiety in cycloadducts **2** could be stereospecifically converted to other functional groups. One approach to achieve this goal is based on the suggested mechanism for the cerium(IV) oxidation. The mechanism for this oxidation is believed to be that shown in eq 2, that is, one-electron oxidation of the formally iron(II) complex to an iron(III) complex, which rapidly undergoes rearrangement to acyl iron(III) complex **4**. Nucleophilic attack on the carbonyl group by methanol followed by loss of the iron moiety leads to the observed esters.[4,5] In support of such a mechanism, migratory insertion of a CO group of methyl iron(II) complexes to give acetyl complexes has been shown[6] to be greatly accelerated on one-electron oxidation. In principle, nucleophiles other than alcohols could be used to attack acyl iron(III) complex **4**. Indeed, chlorine in chloroform converts FpR into acid chlorides, RCOCl,[5] presumably via chloride ion attack on acyl iron(III) complex **4**, and β-amino groups have been reported[7] to intramolecularly attack presumed acyl iron(III) complexes to form β-lactams.[8]

This paper reports the intermolecular trapping of presumed acyl iron(III) complexes by azide ion resulting in the formation of acyl azides. Curtius rearrangement[9] of these compounds provides substituted 7-*syn*-amino-2-norbornenes.[10] Overall this represents a new, selective, stereospecific transformation of the Fp moiety in cycloadducts **2** into an amino group, as shown in eq 3. Such

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(7) Wong, P. K.; Madhavarao, M.; Marten, D. F.; Rosenblum, M. *J. Am. Chem. Soc.* **1977**, *99*, 2823.

(8) β-Lactams have also been synthesized via organoiron intermediates by first effecting thermal rearrangement to an iron chelate followed by oxidation: Berryhill, S. R.; Rosenblum, M. *J. Org. Chem.* **1980**, *45*, 1984; Berryhill, S. R.; Price, T.; Rosenblum, M. *J. Org. Chem.* **1983**, *48*, 158.

(9) (a) Smith, P. A. S. *Org. React. (N.Y.)* **1946**, *3*, 337. (b) Banthorpe, D. V. In *The Chemistry of the Azido Group*; Patai, S., Ed.; Interscience: New York, 1971; pp 397–405. (c) Smith, P. A. S. *Derivatives of Hydrazine and Other Hydronitrogens Having N–N Bonds*; Benjamin: Reading, 1983; pp 272–273.

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0022-3263/86/1951-5123$01.50/0

Table I. Yields of Acyl Azides 5 Formed on Oxidation of Fp Complexes 2 and of Their Curtius Rearrangement Products 6

compound	yield[a] of corresponding 5, %	yield[b] of corresponding 6, %
2, $R^1 = R^4 = CN$, $R^2 = R^3 = H$	82, 60	99
2, $R^1 = R^2 = CN$, $R^3 = R^4 = H$	86, 75	95
2, $R^1 = R^2 = H$, $R^3 = R^4 = CN$	80, 73	94
2, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$	36, 63	60
2, $R^1 = CN$, $R^2 = R^3 = R^4 = H$	25, 40	40
2, $R^3 = CN$, $R^1 = R^2 = R^4 = H$	—, 17	85

[a] First number refers to the yield using bromine in acetonitrile containing sodium azide, and second number is the yield using chlorine in place of bromine. [b] Thermolysis in toluene–*tert*-butyl alcohol (2:1) at 80 °C.

a conversion further enhances the synthetic utility of the cycloaddition reactions of $Fp(\eta^1\text{-}C_5H_5)$ by rendering this reagent the synthetic equivalent of 5-amino-1,3-cyclopentadiene. Furthermore, Diels–Alder reactions of 5-amino-1,3-cyclopentadiene have not been reported to our knowledge.

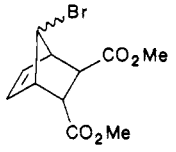
Results and Discussion

Oxidation of cycloadduct **2**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$, with 6 molar equiv of ammonium cerium(IV) nitrate in acetonitrile at 0 °C containing excess sodium azide gave acyl azide **5**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$, isolated in 73% yield as a crystalline solid after workup. Despite the high yield in this case, the most generally useful synthetic method involved use of 2–3 molar equiv of chlorine or bromine as the oxidizing agent rather than ammonium cerium(IV) nitrate.[11] The results are presented in Table I. Note that the iron moiety in cycloadducts **2** reacts in preference to the double bond with halogen and there is no epimerization of the substituents at C(2) or C(3). In addition, this transformation produces only one epimer at C(7) in all cases.

The structures of these acyl azides **5** were established spectroscopically and, in one case, chemically. All of these acyl azides displayed strong infrared absorption at 2145–2173 cm^{-1}, characteristic of the N_3 asymmetric stretching vibration, and at 1699–1709 cm^{-1}, which is characteristic of the carbonyl stretching frequency in acyl azides.[12] The ^1H NMR spectra for acyl azides **5** are recorded with peak assignments in the Experimental Section. These ^1H NMR spectra are remarkably similar to those of the corresponding esters, i.e., **3**.[2,3] Unfortunately, acyl azides **5** proved too unstable to permit elemental analysis. However, the corresponding carbamates obtained from them, as discussed below, gave satisfactory exact masses or elemental analyses.

The overall structure and especially the stereochemistry at C(7) were also proven by chemical means for acyl azide **5**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$. Methanolysis[13] of this material in methanol containing a catalytic amount of potassium carbonate provided a single product. This crystalline ester was isolated in excellent yield. Its IR and ^1H NMR spectra were identical with those of **3**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$, reported previously.[3] In addition, the melting points of the ester prepared by methanolysis and that synthesized as previously reported[3] were the same, and the melting point of an intimate mixture of these two samples was undepressed.

The mechanism for the conversion of the Fp moiety into an acyl azide group has not been studied. However, it is reasonable that in the oxidation of the Fp group with ammonium cerium(IV) nitrate, acyl iron(III) intermediate **4** is formed with retention of configuration at C(7). The iron moiety is then displaced by azide ion to give the acyl azide. With halogen as the oxidant in place of ammonium cerium(IV) nitrate, the mechanism may be similar.[14] Thus, *erythro*-(3,3-dimethylbutyl-1,2-d_2)Fp with bromine in methanol produced the carbonyl insertion product, i.e., the corresponding methyl ester, with retention of configuration.[5] However, chlorine in chloroform converts Fp alkyl compounds into acid chlorides,[5] and acyl halides may be intermediates in the conversion of Fp groups into esters as well as acyl azides with halogen under the reported conditions. Halogens are also known to convert Fp alkyl compounds into alkyl halides.[5,15] We do not observe such products under our reaction conditions except for reaction of Fp complex **2**, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$, with bromine in acetonitrile with sodium azide. In addition to acyl azide **5**, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$, a bromo compound was isolated. The spectroscopic properties of this compound are consistent with a 7-bromo compound **8** of undetermined stereochemistry at C(7). As is apparent



8

from other studies,[15] there are several delicately poised pathways for the course of the reaction of halogens with Fp alkyl compounds.

Thermolysis[16] of each of the acyl azides **5** in a toluene–*tert*-butyl alcohol (2:1) solution at reflux produced the corresponding carbamates **6** isolated in the yields shown in Table I. The structures of the products were assigned by analysis of their IR, ^1H NMR, and mass spectra and elemental analysis. In addition, the configuration at C(7) was assigned on the basis of the known retention of stereochemistry of the migrating carbon atom in the Curtius rearrangement.[9] Selective hydrolysis of carbamate[5] **6**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$, and **6**, $R^1 = R^2 = H$, $R^3 = R^4 = CN$, provided crystalline **7**, $R^1 = R^2 = CN$, $R^3 = R^4 =$

(11) In competition with the oxidation of the Fp compound by cerium(IV) is the oxidation of azide ion. Cerium(IV) salts, including ammonium cerium(IV) nitrate, oxidize azide ion to nitrogen, and this forms the basis of quantitative determination of azide ion: Grove, E. L.; Braman, R. S.; Combs, H. F.; Nicholson, S. B. *Anal. Chem.* **1962**, *34*, 682 and references therein.

(12) Lieber, E.; Oftedahl, E. *J. Org. Chem.* **1959**, *24*, 1014. Nakanishi, K.; Solomon, P. H. *Infrared Absorption Spectroscopy*, 2nd ed.; Holden-Day: San Francisco, 1977; p 23.

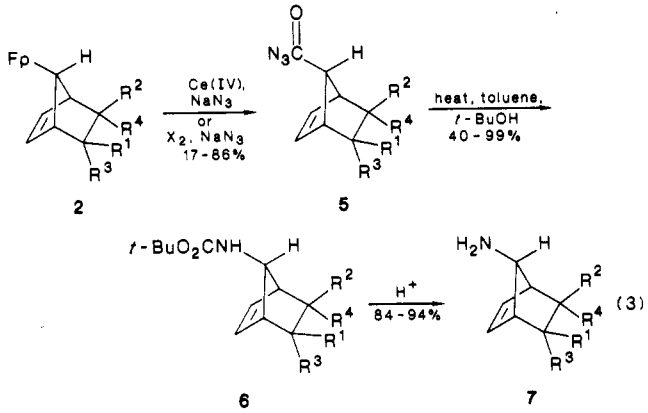
(13) Reference 9c, p 280. Suh, J.; Lee, B. H. *J. Org. Chem.* **1980**, *45*, 3103.

(14) Whether halogen azides are formed under these conditions and their role, if any, in these reactions are unexplored: Hassner, A.; Boerwinkle, F. *J. Am. Chem. Soc.* **1968**, *90*, 216; Hassner, A.; Boerwinkle, F. *Tetrahedron Lett.* **1969**, 3309; Hassner, A. *Acc. Chem. Res.* **1971**, *4*, 9.

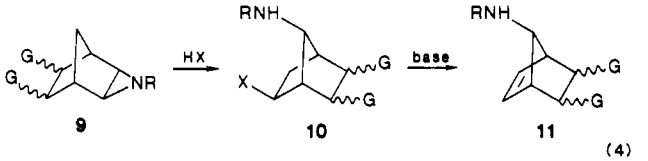
(15) Johnson, M. D. *Acc. Chem. Res.* **1978**, *11*, 57. Rogers, W. N.; Page, J. A.; Baird, M. C. *Inorg. Chem.* **1981**, *20*, 3521.

(16) There is no evidence for intramolecular 1,3-cycloaddition of the acyl azide moiety to the syn double bond in acyl azides **5**. Azides cycloadd readily to the strained double bond in norbornenes: Smith, P. A. S. *Derivatives of Hydrazine and Other Hydronitrogens Having N–N Bonds*; Benjamin: Reading, 1983; pp 283–285 and references therein. But such an intramolecular addition in **5** would give a highly strained product. In addition, there is no evidence for the formation of an acyl aziridine in the thermolysis of acyl azides **5**, or products derived from such an intermediate. Acyl aziridines could result from the addition of an acyl nitrene to the proximate double bond (or decomposition of the 1,2,3-triazoline formed by 1,3-dipolar cycloaddition). However, the thermal Curtius rearrangement of acyl azides is believed to be concerted and not proceed via an acyl nitrene.[9c] Acyl aziridines may form on irradiation of acyl azides **5**.[10b]

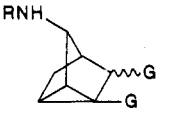
H, in 94% yield and crystalline 7, $R^1 = R^2 = H$, $R^3 = R^4 = CN$, in 84% yield, respectively. The overall reaction is summarized in eq 3.



This reported synthesis of substituted 7-*syn*-amino-2-norbornenes provides an attractive route to these new compounds and substantially expands the known methodology for the synthesis of such compounds.[17] There are only a few reports on the formation of 7-*syn*-amino-2-norbornenes in the literature. Lithium aluminum hydride reduction of the oxime of norbornen-7-one stereoselectively produced 7-*anti*-amino-2-norbornene and only 1% of the 7-syn isomer.[17c] Thermolysis of the triazolines formed from norbornene and methyl azidoformate and phenyl azide yielded mixtures of products containing 7-*syn*-(*N*-carbomethoxy)amino- and 7-*syn*-*N*-phenylamino-2-norbornene, respectively, in low yield.[17b,d] However, acid-catalyzed rearrangement of triazolines afforded better yields of 7-*syn*-amino-2-norbornenes. The adduct of norbornene and phenyl azide,[17e] as well as the adduct of phenyl azide and dicyclopentadiene,[17a] and its dihydro derivative,[17a] on treatment with aqueous acid provided mixtures of products containing 73%, 32%, and 28% yields of the corresponding 7-*syn*-*N*-phenylamino-2-norbornenes, respectively. The most efficient previously reported synthesis of 7-*syn*-amino-2-norbornenes, shown below[17c,f,g] in eq 4, involves



the treatment of aziridines 9[18] with hydrogen halide, followed by dehydrohalogenation with strong base. This method is limited by the requirement of strong acid and strong base. Thus, for the compounds that we have reported, this method is deemed unsuitable. Treatment of **10** in which G is an acidifying group, such as CN or CO_2Me, with base would likely result in preferential proton abstraction α to G and consequent 1,3-elimination to nortricyclene **12**, a well-known favorable pathway in norbornyl derivatives,[19] rather than 1,2-elimination to **11**.



Experimental Section

Melting points were measured on a Thomas-Hoover melting point apparatus and are uncorrected. Solvents were routinely dried by standard procedures[20] and stored under an inert atmosphere. The NMR solvents were predried over 3-Å molecular sieves and stored in a Schlenk flask under an inert atmosphere. In addition, NMR samples were routinely passed through a plug of Celite to remove finely divided decomposition particles. ^1H NMR spectra were measured by using a Varian Model EM-360 spectrometer at 60 MHz and a Bruker Model WM-250 spectrometer at 250 MHz. The chemical shifts are recorded in δ units with internal tetramethylsilane as reference. IR spectra were measured by using a Perkin-Elmer Model 983 spectrophotometer. Mass spectra were run on a Varian MAT 311A mass spectrometer coupled with a Varian SS-200 data system or were done at the Midwest Center for Mass Spectrometry, University of Nebraska, Lincoln, NE (National Science Foundation Regional Instrumentation Facility). Analytical and preparative TLC used Merck HF-254 silica gel purchased from Brinkmann Instruments, Inc. Preparative-layer plates were prepared on 8 × 8 in. glass plates with an absorbent layer 0.75-mm thick. Neutral alumina for medium-pressure LC was purchased from Universal Scientifics, Inc., and deactivated to grade III[21] before use. A column measuring 3 × 20 cm was used for medium-pressure LC. Elemental microanalyses were performed by analysts at Atlantic Microlab, Inc., Atlanta, GA.

The 7-*syn*-Fp cycloadducts **2** were prepared as reported previously.[2,3] Sodium azide was purchased from Ventron Chemical Co. The results were the same whether the sodium azide was used as purchased or after activation.[22] A solution of chlorine in carbon tetrachloride was prepared by saturating the solvent with reagent grade chlorine gas, obtained from Matheson Gas Co., at ambient temperature for 1 h. The concentration of the chlorine in the solution was determined iodometrically.[23]

General Procedures for the Conversion of Fp Cycloadducts 2 into Acyl Azides 5. To a solution of Fp cycloadduct **2** (0.3–1.0 mmol) in acetonitrile (15 mL) was added sodium azide (10 molar equiv). This slurry was stirred for 30 min at ambient temperature and then cooled to 0 °C. At this point any one of three oxidants was added to the reaction mixture as follows. To this vigorously stirred reaction mixture was added ammonium cerium(IV) nitrate (6 molar equiv) in one portion, or a solution of chlorine in carbon tetrachloride (3 molar equiv) over 1 h, or bromine portionwise (0.5 molar equiv in each portion) every 15 min until TLC analysis indicated that all of the starting material had been consumed. In the case of ammonium cerium(IV) nitrate as oxidant, the reaction mixture was stirred for an additional 1 h after completion of the addition, poured into water (60 mL), and extracted with dichloromethane (5 × 30 mL). In the case of halogen as oxidant, the reaction mixture was poured into water (60 mL) immediately after completion of the addition and extracted with dichloromethane (5 × 25 mL). In all cases, the organic extracts were combined, washed successively with water until the washing remained clear (approximately seven times) and brine, dried (anhydrous $MgSO_4$), and filtered through Celite, and the solvent was evaporated at or below ambient pressure to give crude product. In some reactions, the product is contaminated with an orange-red oil. This contaminant was most easily removed

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(18) Aziridine **9**, R = CO_2Et, G = H, was obtained in high yield from the corresponding triazoline, i.e., adduct of norbornene and ethyl azidoformate, on warming in methanol.[17c] Aziridine **9**, R = CN, G = H, was produced in very good yield in the reaction of norbornene with cyanogen azide.[17f] Aziridine **9**, R = SO_2Ph, G = H, was prepared by the reaction of norbornene with benzenesulfonylazide: Zalkow, L. H.; Oelschlager, A. C. *J. Org. Chem.* **1963**, *28*, 3303; Zalkow, L. H.; Oehlschlager, A. C.; Cabot, G. A.; Hale, R. L. *Chem. Ind. (London)* **1964**, 1556.

(19) Hart, H.; Martin, R. A. *J. Org. Chem.* **1959**, *24*, 1267.

(20) Gordon, A. J.; Ford, R. A. *The Chemists' Companion*; Wiley: New York, 1972; pp 429–447.

(21) Reference 9c, p 374.

(22) Smith, P. A. S. *Org. React (N.Y.)* **1946**, *3*, 382.

(23) Skoog, D. A.; West, D. M. *Fundamentals of Analytical Chemistry*, 3rd ed.; Holt, Rinehart, and Winston: New York, 1976.

by dissolving the crude product into a 1:1 (v/v) solution of diethyl ether–hexanes and stirring this solution open to the air for 24–36 h at room temperature. The solution was then filtered through Celite, and the solvent was removed under reduced pressure at or below ambient temperature. Most products were obtained pure by crystallization from the appropriate solvents. Since the products are thermally unstable, all crystallization were performed at or below ambient temperature. The solutions were all concentrated by removing the volatile solvents under a stream of argon. Once crystals began to form, the solutions were cooled to −20 °C for 24 h. The resultant crystals were collected. A second, smaller crop of crystals could be obtained by concentrating the mother liquor and recooling it.

7-*syn*-Azidocarbonylbicyclo[2.2.1]hept-5-ene-2-*exo*,3-*endo*-dicarbonitrile (5, $R^1 = R^4 = CN$, $R^2 = R^3 = H$). Repeated recrystallization from diethyl ether–hexanes provides pure **5**, $R^1 = R^4 = CN$, $R^2 = R^3 = H$: ^1H NMR ($CDCl_3$, 250 MHz) δ 6.39 (dd, 2, J = 1.8, 1.8 Hz, H5, H6), 3.70 (dd, 1, J = 3.4, 1.7 Hz, H4), 3.66 (dd, 1, J = 3.6, 1.7 Hz, H1), 3.27 (dd, 1, J = 4.1, 3.7 Hz, H3-*exo*), 2.90 (m, 1, H7-*anti*), 2.56 (d, 1, J = 4.3 Hz, H2-*endo*); IR (KBr) ν 2243 (C≡N), 2145 (N_3), 1709 (C=O), 1159 cm^{-1}.

7-*syn*-Azidocarbonylbicyclo[2.2.1]hept-5-ene-2-*exo*,3-*exo*-dicarbonitrile (5, $R^1 = R^2 = CN$, $R^3 = R^4 = H$). Repeated recrystallization from diethyl ether–hexanes gives pure **5**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$: ^1H NMR ($CDCl_3$, 250 MHz) δ 6.25 (dd, 2, J = 1.8, 1.8 Hz, H5, H6), 3.68 (dd, 2, J = 3.5, 1.8 Hz, H1, H4), 3.18 (br s, 1, H7-*anti*), 2.75 (s, 2, H2-*endo*, H3-*endo*); IR (KBr) ν 2242 (C≡N), 2173 (N_3), 1709 (C=O), 1202 cm^{-1}.

7-*syn*-Azidocarbonylbicyclo[2.2.1]hept-5-ene-2-*endo*,3-*endo*-dicarbonitrile (5, $R^1 = R^2$ H, $R^3 = R^4 = CN$). Repeated recrystallization from diethyl ether hexanes affords pure **5**, $R^1 = R^2 = H$, $R^3 = R^4 = CN$: ^1H NMR ($CDCl_3$, 250 MHz) δ 6.51 (dd, 2, J = 1.8, 1.8 Hz, H5, H6), 3.69 (dd, 2, J = 3.1, 1.6 Hz, H1, H4), 3.38 (dd, 2, J = 1.7, 1.2 Hz, H2-*exo*, H3-*exo*), 2.54 (dd, 1, J = 1.8, 1.2 Hz, H7-*anti*); IR (KBr) ν 2246 (C≡N), 2155 (N_3), 1701 (C=O), 1177 cm^{-1}.

Dimethyl 7-*syn*-Azidocarbonylbicyclo[2.2.1]hept-5-ene-2-*exo*,3-*endo*-dicarboxylate (5, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$). The crude product obtained by oxidation of **2**, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$, with bromine or chlorine was dissolved in hexane and cooled in a −20 °C bath for 24 h. Crystals were obtained, which after repeated recrystallization provided pure **5**, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$: ^1H NMR ($CDCl_3$, 250 MHz) δ 6.28 (dd, 1, J = 2.9, 5.8 Hz, CH=), 6.09 (dd, 1, J = 2.8, 5.6 Hz, CH=), 3.74 (s, 3, CH_3), 3.66 (s, 3 CH_3), 3.58 (m, 1, H4), 3.44 (dd, 1, J = 4.2, 3.9 Hz, H3-*exo*), 3.40 (m, 1, H1), 2.95 (dd, 1, J = 1.8, 1.4, H7-*anti*), 2.73 (d, 1, J = 4.5 Hz, H2-*endo*); IR (KBr) ν 2154 (N_3), 1726, 1699 (C=O), 1202, 1178 cm^{-1}.

The combined mother liquors were concentrated under reduced pressure to a clear oil. This oil was chromatographed on a silica gel column with a 1:1 (v/v) solution of diethyl ether–hexanes as eluant. A fraction of **8** was obtained: ^1H NMR ($CDCl_3$, 250 MHz) δ 6.15, 5.99 (d, 2, J = 5.6, 4.6 Hz, CH=), 4.14 (br s, 1, H7), 3.73 (s, 3, CH_3), 3.69 (s, 3, CH_3), 3.74–2.95 (m, 4, H1–4); MS, *m/e* (relative intensity) 290 (M^+ + 2, 0.95), 288 (M^+, 0.96), 209 (100).

7-*syn*-Azidocarbonylbicyclo[2.2.1]hept-5-ene-2-*exo*-carbonitrile (5, $R^1 = CN$, $R^2 = R^3 = R^4 = H$). The crude reaction product was purified by chromatography on a column of silica gel with a 4:1 (v/v) solution of hexanes–diethyl ether as eluant. A fraction of purified **5**, $R^1 = CN$, $R^2 = R^3 = R^4 = H$, was obtained as an oil: ^1H NMR ($CDCl_3$, 60 MHz) δ 6.1 (m, 2, H5, H6), 3.3 (m, 1, H1), 2.3–1.1 (m, 3, CH's), 2.8 (m, 1, H4), 3.4 (m, 1, H7-*anti*); IR (KBr) ν 2238 (C≡N), 2142 (N_3), 1714 (C=O), 1171 cm^{-1}.

7-*syn*-Azidocarbonylbicyclo[2.2.1]hept-5-ene-2-*endo*-carbonitrile (5, $R^1 = R^2 = R^4 = H$, $R^3 = CN$). Repeated recrystallization from hexanes gave pure **5**, $R^1 = R^2 = R^4 = H$, $R^3 = CN$: ^1H NMR ($CDCl_3$, 250 MHz) δ 6.34 (dd, 1, J = 3.0, 5.7 Hz, CH=), 6.22 (dd, 1, J = 2.8, 5.6 Hz, CH=), 3.51 (m, 1, H1), 3.32 (m, 1, H4), 2.96 (ddd, 1, J = 3.8, 3.8, 5.5 Hz, H2-*exo*), 2.45 (br s, 1, H7-*anti*), 2.26 (ddd, 1, J = 3.6, 9.4, 13.0 Hz, H3-*exo*), 1.40 (dd, 1, J = 4.1, 12.4 Hz, H3-*endo*); IR (KBr) ν 2236 (C≡N), 2142 (N_3), 1707 (C=O), 1169 cm^{-1}.

Methanolysis of Acyl Azide 5, $R^1 = R^2 = CN$, $R^3 = R^4 = H$. To a solution of acyl azide **5**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$ (34 mg, 0.16 mmol), in methanol (5 mL) was added anhydrous potassium carbonate (2.2 mg, 0.016 mmol). The reaction solution was stirred at ambient temperature for 36 h. The methanol was removed under reduced pressure at ambient temperature, leaving a clear oily solid. To this material was added dichloromethane (10 mL), and the resultant solid–liquid mixture filtered through Celite. An equivalent volume of hexanes was added, and the dichloromethane was removed under a stream of argon until the solution became cloudy. The solution was then cooled to −20 °C for 3 h. The resultant crystals were collected. A second crop of crystals was obtained by concentrating the mother liquor and recooling the solution. The combined crystals were purified by recrystallization from dichloromethane–hexanes, giving 30 mg (93%) of white needles. The ^1H NMR spectrum at 250 MHz, the IR spectrum, and the melting point of this material were identical with those of an authentic sample of ester **3**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$.[3] In addition, the melting point of an intimate mixture of the two samples was undepressed.

General Procedure for the Thermolysis of Acyl Azides 5. A solution of acyl azide **5** (0.05–0.38 mmol) in toluene was added dropwise over 1 h to a 1:2 (v/v) solution of toluene and *tert*-butyl alcohol (15 mL) heated to 80 °C. The solution was heated at 80 °C for an additional 1 h after completion of the addition. The solution was allowed to cool to ambient temperature, and the solvent was removed under reduced pressure by using a rotary evaporator. The crude reaction mixture was then column chromatographed on MPLC grade alumina with the appropriate eluants as described below. Most products were further purified by recrystallization.

7-*syn*-[(*tert*-Butyloxycarbonyl)amino]bicyclo[2.2.1]-hept-5-ene-2-*exo*,3-*endo*-dicarbonitrile (6, $R^1 = R^4 = CN$, $R^2 = R^3 = H$). The crude product from the thermolysis of acyl azide **5**, $R^1 = R^4 = CN$, $R^2 = R^3 = H$ (29 mg, 0.14 mmol), was eluted from the LC column with diethyl ether. Recrystallization from diethyl ether–hexanes yielded white crystals of carbamate **6**, $R^1 = R^4 = CN$, $R^2 = R^3 = H$ (35 mg, 99%): mp 159–160 °C; ^1H NMR ($CDCl_3$, 250 MHz) δ 6.37 (m, 2, CH=), 4.73 (m, 1, N*H*), 4.10 (m, 1, H7-*anti*), 3.41 (m, 1, H4), 3.30 (m, 1, H1), 3.27 (dd, 1, J = 3.8, 4.5 Hz, H3-*exo*), 2.45 (d, 1, J = 4.5 Hz, H2-*endo*), 1.41 (s, 9, $(CH_3)_3C$); IR (KBr) ν 3244 (NH), 2246 (C≡N), 1694 (C=O), 1165, 1399, 1370 cm^{-1}. Anal. Calcd for $C_{14}H_{17}N_3O_2$: C, 64.84; H, 6.61; N, 16.21. Found: C, 64.56; H, 6.67; N, 16.10.

7-*syn*-[(*tert*-Butyloxycarbonyl)amino]bicyclo[2.2.1]-hept-5-ene-2-*exo*,3-*exo*-dicarbonitrile (6, $R^1 = R^2 = CN$, $R^3 = R^4 = H$). The crude product from the thermolysis of acyl azide **5**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$ (51 mg, 0.24 mmol), was eluted from the LC column with diethyl ether. Recrystallization from diethyl ether–hexanes gave white crystals of carbamate **6**, $R^1 = R^2 = CN$, $R^3 = R^4 = H$ (59 mg, 95%): mp 214–215.5 °C; ^1H NMR ($CDCl_3$, 250 MHz) δ 6.23 (m, 2, CH=), 4.69 (m, 1, N*H*), 4.32 (m, 1, H7-*anti*), 3.37 (br s, 2, H1, H4), 2.66 (s, 2, H2-*endo*,H3-*endo*), 1.51 (s, 9, $(CH_3)_3C$); IR (KBr) ν 3333 (NH), 2242 (C≡N), 1683 (C=O), 1167, 1527, 1258 cm^{-1}. Anal. Calcd for $C_{14}H_{17}N_3O_2$: C, 64.84; H, 6.61; N, 16.12. Found: C, 64.57; H, 6.59; N, 16.01.

7-*syn*-[(*tert*-Butyloxycarbonyl)amino]bicyclo[2.2.1]-hept-5-ene-2-*endo*,3-*endo*-dicarbonitrile (6, $R^1 = R^2 = H$, $R^3 = R^4 = CN$). The crude product from the thermolysis of acyl azide **5**, $R^1 = R^2 = H$, $R^3 = R^4 = CN$ (80 mg, 0.38 mmol), was eluted from the LC column with dichloromethane. Recrystallization from dichloromethane–hexanes afforded white, crystalline carbamate **6**, $R^1 = R^2 = H$, $R^3 = R^4 = CN$ (92.4 mg, 94%): mp 220–227 °C dec; ^1H NMR ($CDCl_3$, 250 MHz) δ 6.50 (m, 2, CH=), 4.74 (m, 2, N*H*), 3.75 (br d, 1, J = 9.1 Hz, H7-*anti*), 3.37 (s, 2, H2-*exo*, H3-*exo*), 3.35 (br s, 2, H1, H4), 1.38 (s, 9, $(CH_3)_3C$); IR (KBr) ν 3442 (NH), 2246 (C≡N), 1703 (C=O), 1163, 1514, 1243 cm^{-1}. Anal. Calcd for $C_{14}H_{17}N_3O_2$: C, 64.84; H, 6.61; N, 16.21. Found: C, 64.70; H, 6.64; N, 16.15.

Dimethyl 7-*syn*-[(*tert*-Butyloxycarbonyl)amino]bicyclo[2.2.1]hept-5-ene-2-*exo*,3-*endo*-dicarboxylate (6, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$). The crude product from the thermolysis of acyl azide **5**, $R^1 = R^4 = CO_2Me$, $R^2 = R^3 = H$ (45 mg, 0.17 mmol), was eluted from the LC column with diethyl ether. The solvent was removed under reduced pressure, yielding a clear oil (33 mg, 60%): ^1H NMR ($CDCl_3$, 250 MHz) δ 6.22 (dd, 1, J = 2.8, 5.4 Hz, CH=), 6.02 (dd, 1, J = 2.8, 5.4 Hz, CH=), 4.77 (m, 1, N*H*), 4.00 (m, 1, H7-*anti*), 3.45 (dd, 1, J = 4.2, 4.3 Hz, H3-*exo*), 3.26 (m, 1, H4), 3.10 (m, 1, H1), 2.63 (d, 1, J = 4.8 Hz, H2-*endo*), 1.39 (s, 9, $(CH_3)_3C$); IR (neat) ν 3386 (NH), 1732 (C=O), 1175, 1206

cm^{-1}; MS, m/e calcd for $C_{16}H_{23}NO_6$: 325.1526. Found: 325.1491.

7-*syn*-[(*tert*-Butyloxycarbonyl)amino]bicyclo[2.2.1]-hept-5-ene-2-*exo*-carbonitrile (6, R^1 = CN, R^2 = R^3 = R^4 = H). The crude product from the thermolysis of acyl azide **5**, R^1 = CN, R^2 = R^3 = R^4 = H (30 mg, 0.16 mmol), was eluted from the LC column with diethyl ether. The solvent was removed under reduced pressure to afford carbamate **6**, R^1 = CN, R^2 = R^3 = R^4 = H, as a white solid (14 mg, 40%): mp 134–136 °C; ^1H NMR ($CDCl_3$, 250 MHz) δ 6.16 (dd, 1, J = 3.0, 5.7 Hz, CH=), 6.03 (dd, 1, J = 3.0, 5.7 Hz, CH=), 4.72 (m, 1, N*H*), 4.04 (m, 1, H7-*anti*), 3.13 (br s, 1, H1), 3.00 (m, 1, H4), 2.18–2.01 (m, 3, H2-*endo*, H3-*endo*, H3-*exo*); 1.23 (s, 9, $(CH_3)_3C$); IR (KBr) ν 3255 (NH), 2236 (C≡N), 1696 (C=O), 1164, 1382, 1365 cm^{-1}; MS, m/e calcd for $C_{13}H_{18}N_2O_2$: 234.1368. Found: 234.1375.

7-*syn*-[(*tert*-Butyloxycarbonyl)amino]bicyclo[2.2.1]-hept-5-ene-2-*endo*-carbonitrile (6, R^1 = R^2 = R^4 = H, R^3 = CN). The crude product from the thermolysis of acyl azide **5**, R^1 = R^2 = R^4 = H, R^3 = CN (7 mg, 0.04 mmol), was eluted from the LC column with diethyl ether. The solvent was removed under reduced pressure to give carbamate **6**, R^1 = R^2 = R^4 = H, R^3 = CN, as a white solid (7.3 mg, 85%): ^1H NMR ($CDCl_3$, 250 MHz) δ 6.33 (dd, 1, J = 2.9, 5.7 Hz, CH=), 6.19 (dd, 1, J = 2.7, 5.7 Hz, CH=), 4.78 (m, 1, N*H*), 3.67 (d, 1, J = 9.1 Hz, H7-*anti*), 3.17 (m, 1, H1), 2.97 (dd, 1, J = 3.9, 7.7 Hz, H2-*exo*), 2.93 (d, 1, J = 3.7 Hz, H4), 2.25 (ddd, 1, J = 3.6, 0.2, 12.8 Hz, H3-*exo*), 1.39 (s, 9, $(CH_3)_3C$), 1.28 (dd, 1, J = 4.3, 12.4 Hz, H3-*endo*); IR (KBr) ν 3257, 3123 (NH), 2239 (C≡N), 1687 (C=O), 1399, 1367, 1164 cm^{-1}; MS, m/e calcd for $C_{13}H_{18}N_2O_2$: 234.1368. Found: 234.1359.

Preparation of 7-*syn*-Aminobicyclo[2.2.1]hept-5-ene-2-*exo*,3-*exo*-dicarbonitrile (7, R^1 = R^2 = CN, R^3 = R^4 = H). A solution of carbamate **6**, R^1 = R^2 = CN, R^3 = R^4 = H (38.7 mg, 0.15 mmol), and *p*-toluenesulfonic acid (36.2 mg, 0.19 mmol) in acetonitrile (20 mL) was stirred at ambient temperature for 15 h. The reaction mixture was dissolved in dichloromethane (25 mL), washed with a saturated aqueous sodium bicarbonate solution, dried over anhydrous magnesium sulfate, filtered through Celite, and concentrated under reduced pressure. The crude product was recrystallized from dichloromethane–hexanes, yielding amine **7**, R^1 = R^2 = CN, R^3 = R^4 = H, as a white solid (22.4 mg, 94%): mp 129–131 °C; ^1H NMR ($CDCl_3$, 250 MHz) δ 6.23 (br s, 2, CH=), 3.75 (br s, 1, H7-*anti*), 3.20 (br s, 2, H1, H4), 2.60 (s, 2, H2-*endo*, H3-*endo*), 1.35 (m, s, N*H*); IR (KBr) ν 3388, 3326 (NH_2), 2240 (C≡N), 1260 cm^{-1}; MS, m/e calcd for $C_9H_9N_3$: 159.0798. Found: 159.0783.

Preparation of 7-*syn*-Aminobicyclo[2.2.1]hept-5-ene-2-*endo*,3-*endo*-dicarbonitrile (7, R^1 = R^2 = H, R^3 = R^4 = CN). A solution of carbamate **6**, R^1 = R^2 = H, R^3 = R^4 = CN (14.7 mg, 0.057 mmol), and *p*-toluenesulfonic acid (26.4 mg, 0.14 mmol) in acetonitrile (10 mL) was stirred at room temperature for 15 h. The reaction mixture was dissolved in dichloromethane (25 mL), washed with a saturated aqueous sodium bicarbonate solution, dried over anhydrous magnesium sulfate, filtered through Celite, and concentrated under reduced pressure. The crude product was recrystallized from dichloromethane–hexanes yielding amine **7**, R^1 = R^2 = H, R^3 = R^4 = CN, as a white solid (7.6 mg, 84%): mp 146–147 °C; ^1H NMR ($CDCl_3$, 250 MHz) δ 6.49 (br s, 2, CH=), 3.31 (dd, 2, J = 1.9, 1.25 Hz, H2-*exo*, H3-*exo*), 3.21 (br s, 2, H1, H4), 3.07 (br s, 1, H7-*anti*), 1.45 (br s, NH_2); IR (KBr) ν 3368, 3315 (NH_2), 2240 (C≡N), 1590, 1355, 1271, 1144, 990, 932, 878, 780, 762 cm^{-1}; MS, m/e calcd for $C_9H_9N_3$: 159.0798. Found: 159.0781.

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Synthesis of Spherands with Functional Groups at the Outer Sphere

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Three novel spherands (**10a–c**) have been synthesized by the oxidative coupling reaction of the corresponding dilithioterphenyls in yields of 12–17%. The compounds have been isolated as the corresponding LiCl complexes. Two of these spherands (**10a** and **10b**) have two functional groups at the outer sphere (OCH_3 or OCH_2OCH_3), whereas the third compound (**10c**) has two reactive positions that allow further reaction in the outer sphere. A spherand with two *N*,*N*-dibenzyl groups at the outer sphere (**10d**) was obtained in low yield. The starting terphenyls (**8c,d,f,h**) were prepared from a common intermediate (**7a**) by the appropriate modification of the nitro group and methylation of the hydroxyl group. Compound **7a** was synthesized in nine steps from 4-methylanisole (**2**) via the condensation of nitromalondialdehyde with the 1,3-diphenyl-2-propanone (**6b**). The spherand–lithium chloride complexes were characterized by ^1H and ^{13}C NMR spectroscopy and mass spectrometry.

Introduction

In 1979 Cram et al.[1] reported the synthesis of a novel class of macrocyclic host molecules that have rigid pre organized cavities and are composed of at least six anisyl units. These so-called spherands form very stable complexes with small alkaline cations (Li^+, Na^+). The high thermodynamic stabilities ($K_a > 10^{14}$ L mol^{-1}) are due to the rigidity of the molecular framework which enforces a high electron density in the cavity, which is composed of the anisyl moieties. Upon complexation the electron–electron repulsion of neighboring oxygen lone pairs is relieved. This is a fundamentally different concept compared with the complexation of cations by flexible macrocyclic polyligands,[2] that requires reorganization of the ligand prior to or during complexation, although also in the complexation of cations by crown-ethers, relief of oxygen–oxygen repulsions may contribute.[3] In a series of papers[4] the concept of preorganization was further ex-

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