and after being allowed to stand for 5 min, the mixture was titrated with 0.01 N $Na_2S_2O_3$.

The iodine was determined by titration with aqueous $Na_2S_2O_3$ after addition of the sample solution (2 mL) to 4 N H_2SO_4 (30 mL)–saturated KI (1 mL).

The reaction products were analyzed with a Yanagimoto G 180 gas chromatograph using Bentone 34-DIDP (5 + 5%), PEG 20M, and Porapak QS columns. The identification of products was done by comparison of GLC peaks with those of the authentic samples and by GC/MS (JEOL JMS-D300 mass spectrometer). The yields were estimated by GLC with mesitylene as an internal standard.

Photolysis. The solution of methyl iodide (0.1–0.2 M) in aromatic solvents were irradiated by a Halos 30- or 60-W low-pressure Hg lamp in a cylindrical 10 × 200 mm quartz cell or a Halos 1-kW or 300-W high-pressure Hg lamp in a Pyrex cell. Low-temperature experiments at –70 to –20 °C were conducted by cooling a reaction cell with a Yamato Neocool DIP Model BD-21 cooling apparatus.

Analyses of Gaseous Products. The gaseous products evolved by photolysis were collected in a gas buret (50-mL volume) connected with a capillary tube to the photolysis vessel and were replaced with He. The gas collected was analyzed by GC/MS and GLC with two sorts of columns packed with Porapak Type T and Porapak Type QS, and analyses of mass peaks were carried out by comparison with standard samples.[18] Ethane was not detected in the gas in both the 254- and >290-nm irradiations.

Registry No. Toluene, 108-88-3; anisole, 100-66-3; ethylbenzene, 100-41-4; benzene, 71-43-2; MeI, 74-88-4.

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(18) Stenhagen, E.; Abrahamsson, S.; McLafferty, F. W. "Resistry of Mass Spectral Data"; 1974; Vol. 1.

Trisannelated Benzenes. Preparation, Properties, and Photoelectron Spectra

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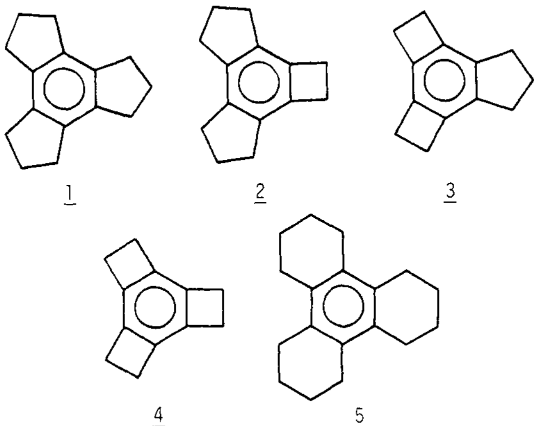
The preparation of tricyclobutabenzene and its next two higher homologues is described. The synthetic approach involves the [4 + 2] cycloaddition of dimethyl 1,2-cyclobutenedicarboxylate to an appropriate diene followed by hydrolysis of the ester functions, bisdecarboxylation, and aromatization. The NMR, ultraviolet, and photoelectron spectra of these small-ring trisannelated benzenes are presented. The properties of all three molecules are reasonably consistent, and no evidence is shown for any serious perturbation of aromaticity.

Until recently, the smallest known trisannelated benzene system was trindan (tricyclopentabenzene, 1). Our preparation of a series of bisannelated benzenes[1] and study of their properties[2] has consequently led us to consider the lower homologues of trindan, 2–4 (Chart I). Beyond the synthetic challenge involved, we were also interested in the interaction of reactive, strained ring systems with resonance-stabilized aromatic nuclei.[3] This paper describes the general synthetic approach to trisannelated benzenes and some of the more salient physical properties of these systems.

Synthesis

Trindan (1) was first reported in 1897 as a minor product of the action of HCl on cyclopentanone.[4] Although this condensation approach has been used in the preparation of several trisannelated benzenes, it is unsatisfactory for the preparation of 4 as well as unsymmetrical analogues. A second approach to symmetrical trisannelated benzenes is the cyclotrimerization of a cycloalkyne. Molecules such as trinorbornabenzene[5] and tribullvalenobenzene[6] have been prepared in this manner. The unlikelihood of generating cyclobutyne makes this route unsatisfactory for the synthesis of 4. A notable exception, however, is the copper–bronze-promoted cyclization of 1,2-diiodoperfluorocyclobutene which provides the perfluoro analogue of 4 in reasonably good yield.[7]

Chart I



There have been several recent reports of pyrolytic reactions which might have led to the formation of tricylo-

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‡ University of Houston.

(1) (a) R. P. Thummel, *J. Am. Chem. Soc.*, **98**, 628 (1976). (b) R. P. Thummel and W. Nutakul, *J. Org. Chem.*, **42**, 300 (1977). (c) See also R. P. Thummel, *Acc. Chem. Res.*, **13**, 70 (1980).

(2) (a) R. P. Thummel, K. Houk, W. Nutakul, W. E. Cravey, C. Santiago, and R. W. Gandour, *J. Am. Chem. Soc.*, **100**, 3730 (1978); (b) R. P. Thummel and W. Nutakul, *J. Org. Chem.*, **43**, 3170 (1978).

(3) R. P. Thummel, submitted for publication in *Isr. J. Chem.* See also the references cited therein.

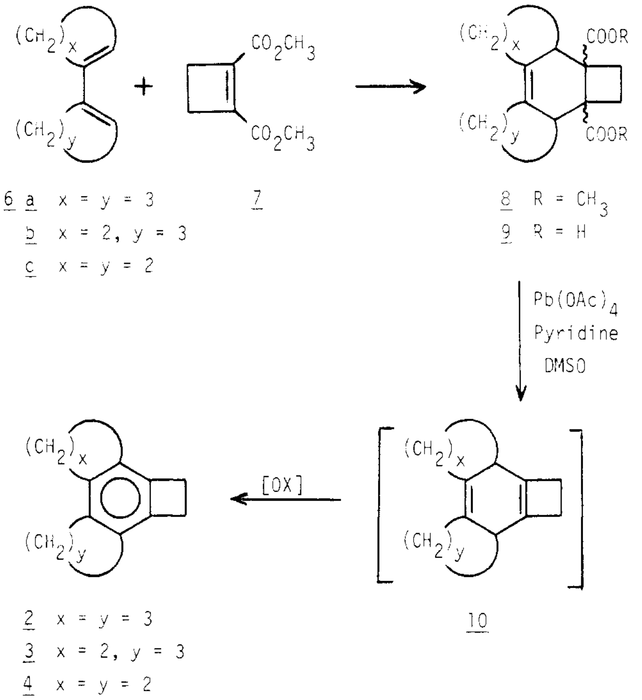
(4) A. Wallach, *Chem. Ber.*, **30**, 1096 (1897).

(5) P. G. Gassman and I. Gennick, *J. Am. Chem. Soc.*, **102**, 6863 (1980).

(6) E. Schroder and J. F. M. Oth, *Angew. Chem., Int. Ed. Engl.*, **6**, 414 (1967).

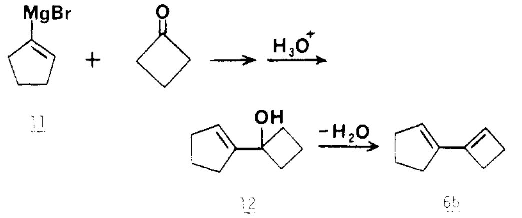
(7) R. L. Soulen, S. K. Choi, and J. D. Park, *J. Fluorine Chem.*, **3**, 141 (1973).

Scheme I



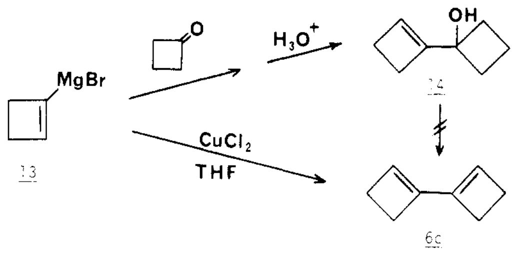
butabenzene.[8] In every case, hexaradialene is instead produced, often as the sole or major product. It has been speculated that tricyclobutabenzene might be thermally unstable and thus impossible to prepare under high-temperature conditions. For this reason we have pursued a cycloaddition approach to molecules **2–4** in which the final steps are carried out at lower temperature to ensure that the annelated cyclobutene rings do not cleave to give exocyclic methylenes.

Scheme I outlines our general route to trisannelated benzenes. We have previously described the detailed synthesis of **2**.[9] Preparation of the two lower homologues is directly analogous if one substitutes the appropriate dienes **6b** and **6c**. Both these dienes are prepared differently from the simple two-step pinacol approach used to prepare **6a**.[10] The Grignard addition of 1-cyclopentenylmagnesium bromide to cyclobutanone provided a 69% yield of the tertiary alcohol **12**. Iodine-promoted



dehydration of **12** gave only low yields of **6b**. Employment of potassium bisulfate, however, led smoothly to the desired diene in 60% yield. This material was extremely reactive and had to be used immediately in the subsequent cycloaddition step which proceeded smoothly in 78% yield.

We initially attempted to prepare 1,1′-dicyclobutenyl (**6c**) by a similar dehydration of the allylic alcohol **14**. This

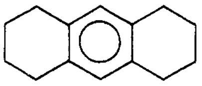


material could be obtained in 46% yield by the Grignard reaction of 1-cyclobutenyl magnesium bromide with cyclobutanone. All attempts at dehydration, however, led only to polymeric material. At this time, we became aware of the work of Lüttke and Heinrich in which they prepare diene **6c** by the copper(II) chloride promoted coupling of the Grignard species **13**.[11] Following their procedure and exercising a good deal of care to exclude heat, acid, and oxygen as much as possible, we were able to produce **6c** as a solid (mp ~5 °C) in 41% yield.[12] As with **6b**, diene **6c** is immediately reacted with 1 equiv of diester **7** in a sealed glass tube at 110 °C for 12 h. A 60% yield of **8c** is obtained as an 81:19 mixture of two isomeric materials presumed to be the exo and endo Diels–Alder adducts. Although both ester functions in the diesters **8** are of the neopentyl type, in all cases they were smoothly converted to the corresponding dicarboxylic acids **9** in good yield.

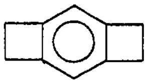
The bisdecarboxylation and subsequent oxidation were effected by treatment of the diacid **9** with lead tetraacetate in dimethyl sulfoxide with pyridine added to scavenge the acetic acid which is generated. In each case, a mildly exothermic reaction was observed accompanied by copious gas evolution. Normally, 2 equiv of lead tetraacetate is employed in this process such that the intermediate 1,4-cyclohexadiene is not isolated but rather oxidized directly to the desired aromatic species. Under similar conditions, we have observed that 1,4-cyclohexadiene is converted smoothly into benzene. Since treatment of **9c** under these conditions afforded only 0.5% of tricyclobutabenzene, we repeated the reaction employing only 1 equiv of lead tetraacetate. Chromatography of the reaction product provided an oil which showed a complex NMR spectrum not inconsistent with structure **10c** (seven nonequivalent hydrogens). After treatment with DDQ the NMR spectrum reduced to a single line at 3.12 ppm, and the yield increased to 3.5%. The fate of the remaining organic material in these oxidative decarboxylations is still unknown, although it is not unlikely that further oxidation to benzoic acid derivatives might occur.

Properties

The proton NMR spectra of **1–4** are very self-consistent. The cyclopentene α-methylene protons resonate at 2.69–2.73 ppm and cyclobutene α-methylenes at 3.04–3.12 ppm. It is interesting to compare the aromatic carbon resonances of **4** (138.5 ppm) and dodecahydrotriphenylene (**5**, 132.5 ppm). We have invoked rehybridization effects to explain the difference in chemical shift of the substituted aromatic carbon of **15** (129.3 ppm) vs. that of **16**



15



16

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[8] (a) A. J. Barkovitch, E. S. Strauss, and K. P. C. Vollhardt, *J. Am. Chem. Soc.*, **99**, 8321 (1977); (b) L. G. Harruff, M. Brown, and V. Boekelheide, *ibid.*, **100**, 2893 (1978). (c) P. Schiess and M. Heitzmann, *Helv. Chim. Acta*, **61**, 844 (1978).

[9] (a) R. P. Thummel, *J. Chem. Soc., Chem. Commun.*, 899 (1974); (b) J. D. Korp, R. P. Thummel, and I. Bernal, *Tetrahedron*, **33**, 3069 (1977).

[10] D. S. Greidinger and D. Ginsburg, *J. Org. Chem.*, **22**, 1406 (1957).

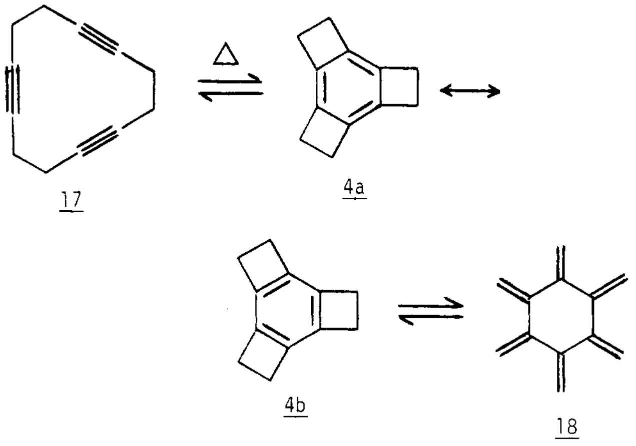
[11] (a) F. Heinrich, Ph.D. Thesis, University of Göttingen, 1972; (b) F. Heinrich and W. Lüttke, *Justus Liebigs Ann. Chem.*, 1880 (1978).

[12] W. Nutakul, R. P. Thummel, and A. D. Taggart, *J. Am. Chem. Soc.*, **101**, 770 (1979).

(143.4 ppm). Systems **1** and **5** have three-fold symmetry which tends to cancel out some of these polarization effects leading to less of a difference in the resonances of corresponding carbon atoms even though the differences in strain are presumably greater. It is interesting to note that the aromatic carbon resonance of trindan (**1**) at 137.5 Hz is much closer to that of **4** than that of **5**. This same trend is evident in the simple benzocycloalkenes and offers some evidence that the strain associated with cyclopentene fusion is not much less than that associated with cyclobutene fusion.

The ultraviolet spectra of **1**–**4** are summarized in Table I. Three principal bands are observed for each compound (two bands were not recorded for **3**), and the long-wavelength band shows some vibrational fine structure in each case. There does not appear to be any pronounced variation in the energy of these absorptions except in the case of tricyclobutabenzene (**4**) for which the bands appear at somewhat shorter wavelengths. More suprisingly, the extinction coefficients of these bands do not vary significantly as the size of the annelated rings is decreased. This behavior is different from monoannelated and bisannelated systems where the intensity of the absorptions increases as the size of the fused ring is decreased.[16] If the magnitude of the extinction coefficient is related to the planarity and rigidity of the ground state,[13] then one would again expect tricyclobutabenzene to show stronger bands with enhanced resolution. However, the long-wavelength band for this molecule is the least intense and the least resolved. The planarity of the molecule is evidenced, however, by its ability to pack more tightly into a crystal lattice as reflected by a melting point which exceeds those of its two higher homologues by about 50 °C.

Tricyclobutabenzene is particularly interesting in that it belongs to the family of $C_{12}H_{12}$ hydrocarbons, two of which have recently been shown to be interconvertible. Vollhardt and co-workers have reported that pyrolysis of **17** at 650 °C leads to the formation of small amounts of **18** and have suggested tricyclobutabenzene (**4**) as a likely intermediate.[8a] The inability of these workers to detect any tricyclobutabenzene in this process, as well as other approaches leading to hexaradialene, caused them to speculate that **4** might be thermally less stable than **18**. Our preparation of **4** has demonstrated that the molecule is quite stable. Its stability at higher temperatures was investigated by monitoring its disappearance in the injection port of a gas chromatograph. From the results shown in Table II, it may be seen that the prolonged existence of tricyclobutabenzene at temperatures in excess of 325 °C is unlikely.



17

4a

4b

18

Table I. Ultraviolet Absorption Data for Trisannelated Benzenes[a,b]

1	2	3	4
276 (178)	278 (280)	275 (250)	269 (170)
272 (203)	275 (330)	272 (310)	265 sh (190)
269 (229)	268 (400)	267 (380)	262 (210)
267 (242)	265 (380)	264 (360)	258 (195)
264 (216)	260 (350)	261 (320)	254 (195)
261 (199)			251 sh (170)
			247 sh (150)
230 (7320)	227 (6750)		222 (5600)
			217 sh (6200)
203 (59 900)	205 (36 900)		201 (25 500)

[a] In nanometers, with ϵ values in parentheses. The horizontal arrangement of absorption values is not meant to imply any direct correlation of vibrational structure.
[b] All recorded in isooctane except **3** which was recorded in 95% ethanol.

Table II. Thermal Stability of Tricyclobutabenzene (TCB)

injection port temp, °C	% TCB remaining[a]
325	100
345	50
380	10

[a] Measured vs. naphthalene as an internal standard.

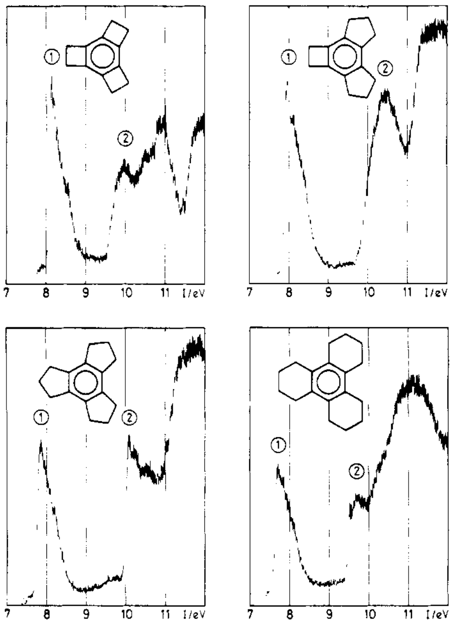


Figure 1. He(Iα) photoelectron spectra of trisannelated benzenes. The ionization energies (I_j^m, in electron volts) shown below refer to the band maxima. The estimated limit of error is ±0.05 eV if the second decimal is given as a subscript and ±0.1 eV if only one decimal place is given. The small maximum close to 9.8 eV in the spectrum of **1** is due to an impurity.

band	4	2	1	5
1, I_1^m	8.1_5	7.9_5	7.8_5	7.7_0
2, I_2^m	~10.0	~10.5	10.1_0	9.5_5

Photoelectron Spectra

The photoelectron spectra of the trisannelated benzenes **1**, **2**, **4**, and **5** are presented in Figure 1 and exhibit a first band system, labeled 1, around 8 eV, corresponding to the ejection of an electron from the two highest occupied π orbitals, which are related to the degenerate $1e_{1g}(\pi)$ orbitals of the parent hydrocarbon benzene (vertical ionization

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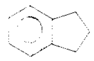
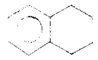
(13) W. R. Moore, E. Marcus, S. E. Fenton, and R. T. Arnold, *Tetrahedron*, 5, 179 (1959).

Table III. Calculation and Comparison of the Shift of the First Ionization Potential of Trisannelated Benzenes

compd	I_1	I_2	$\bar{I}$	δI_{BCA}	compd	δI(obsd)	$3\delta I_{BCA}$
	8.66	9.20	8.93	0.32	1	1.1_0	0.96
	8.46	9.04	8.75	0.50	4	1.4_0	1.50
	8.44	8.96	8.70	0.55	5	1.5_5	1.65

energy $I_1(1e_{1g}) = 9.25$ eV[14]). The Franck–Condon envelopes of all four band systems 1 are practically identical with those observed for the corresponding bands in the photoelectron spectra of hexamethylbenzene (D_{6h} symmetry, neglecting the local methyl group conformations; $I_1 = 7.8_5$ eV[15]) or of hexacyclopropylbenzene (D_{3d} symmetry[16]; $I_1 = 7.7_5$ eV[17]). This suggests that from a photoelectron spectroscopic point of view, **1** and **5** may be regarded to assume an average D_{3h} symmetry and that even **2** behaves as if it possessed a threefold axis. Consequently, the characteristic skew envelopes of the band systems 1 can be explained as being due to the (quasi) Jahn–Teller distortion of the corresponding radical cations.

The position of band systems 1 is shifted by $-1.2_5 \pm 0.2_5$ eV relative to the $1e_{1g}$ band of benzene, as a consequence of the hyperconjugative interaction of the benzene π orbitals with the σ orbitals of appropriate symmetry localized in the cycloalkene moieties. This type of interaction has been observed and discussed previously in context with the photoelectron spectra of cycloalkenes[18] and benzocycloalkenes.[19] For the former set of compounds this interaction has also been examined in more detail by ab initio model calculations.[20] Although these calculations have shown that the situation is not quite as simple as one might have expected, the present results can be easily rationalized by relating them to those obtained for the benzocycloalkenes[19] through naive molecular orbital considerations.

Assuming that the interaction of a methylene pseudo-π orbital, attached to the center μ of the benzene ring, with an atomic 2p orbital in this position is represented by a resonance integral β, we find according to a second-order perturbation calculation that the benzene π orbitals are destablized by $\delta\epsilon = (c_\mu\beta)^2/\Delta\epsilon$ per CH_2 group, where c_μ is the 2p coefficient of the linear combination at the center μ and $\Delta\epsilon$ is the energy gap between the benzene π and the CH_2 pseudo-π orbitals. It is easy to show that the mean ionization energy, $\bar{I} = (I_1 + I_2)/2$, of the first two π bands in the photoelectron spectrum of a benzocycloalkene (BCA) should be shifted by $\delta I_{BCA} = \beta^2/(3\Delta\epsilon)$ relative to $I_1 = 9.25$ eV of the first band of benzene. Accordingly, the observed shift, $\delta I(\text{obsd}) = 9.25$ eV - I_1, of band 1 in the spectra of **1**, **4**, and **5** should be equal to $\delta I = 3\,\delta I_{BCA} = \beta^2/\Delta\epsilon$. As shown in Table III, this is indeed what is observed, within the limits of error of the method.

For the less symmetrical compound **2** one finds $\delta I(\text{obsd}) = 1.3_0$ eV, in perfect agreement with the expected value obtained by adding the shift δI_{BCA} for benzocyclobutene to twice the shift for indan, i.e., [0.32 + 2(0.50)] eV = 1.32 eV.

One of the phenomena which one might have wished had made itself felt in the photoelectron spectra of the compounds **1**, **2**, **4**, and **5** concerns the tendency toward double bond localization, i.e., the manifestation of what has been called the Mills–Nixon effect. As is obvious from the spectra shown in Figure 1, nothing of the kind is observed, and this was to be expected in view of our earlier observations.[18,19] In fact, photoelectron spectroscopy is a poor tool for answering questions about "aromaticity" as can be illustrated by the following, perhaps oversimplified, but illuminating example. From an analysis of the photoelectron spectra of polyenes[22] and cyclopolyenes[23] in terms of localized two-center π orbitals, it is deduced that the self-energy of a double bond π orbital, flanked by two others (e.g., the central orbital of hexatriene), is $A(\pi) = -10.0$ eV. The cross term between two conjugated π orbitals is found to be $B = -1.2$ eV, by using the photoelectron spectrum of hexatriene for calibration purposes.[22] If these parameters are used to predict the ionization energy of a hypothetical cyclohexatriene with *strictly* localized double bonds, a value of $I_1 = -(A - B) = 8.8$ eV is obtained. This is only 0.45 eV smaller than the ionization energy of benzene ($I_1 = 9.25$ eV). Thus it is obvious that a small *partial* localization, as might be present in the compounds **1**, **2**, and **4**, would yield shifts of the order of at best ~0.1 eV or less, i.e., shift contributions which are completely swamped by those due to hyperconjugation, larger by at least an order of magnitude.

Experimental Section

Dimethyl sulfoxide was distilled under vacuum from calcium hydride. Pyridine was distilled from barium oxide. Just prior to use, lead tetraacetate was recrystallized from acetic acid and protected from oxygen and light. DDQ was recrystallized from benzene/chloroform. Proton and carbon nuclear magnetic resonance spectra were obtained on a Varian Associates T-60 or XL-100[24] spectrometer, and chemical shifts are reported in parts per million downfield from Me_4Si. Infrared spectra were obtained on a Beckman IR-4250 spectrometer. Mass spectra were obtained by direct sample introduction into a Hewlett-Packard 5933 A gas chromatograph–mass spectrometer system. High-resolution mass spectral analyses were performed by Dr. R. Grigsby at the Department of Biochemistry and Biophysics, Texas A&M University, on a CEC21-110B double-focusing magnetic sector spectrometer at 70 eV. Exact masses were determined by peak matching. All melting points are uncorrected.

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(14) D. W. Turner, C. Baker, A. D. Baker, and C. R. Brundle, "Molecular Photoelectron Spectroscopy", Wiley-Interscience, London, 1970.

(15) M. Klessinger, *Angew. Chem. Int. Ed. Engl.*, 11, 525 (1972). J. P. Maier and D. W. Turner, *J. Chem. Soc., Faraday Trans. 2*, **69**, 196 (1973). Cf. also ref 21.

(16) I. Bar, J. Bernstein, and A. Christensen, *Tetrahedron*, **33**, 3177 (1977).

(17) J. Q. Wang, E. Honegger, E. Heilbronner, and A. Schmelzer, *Sci. Sin.* (Engl. *Ed.*), in press.

(18) P. Bischof and E. Heilbronner, *Helv. Chim. Acta*, **53**, 1677 (1970).

(19) F. Brogli, E. Giovannini, E. Heilbronner, and R. Schurter, *Chem. Ber.*, **106**, 961 (1973).

(20) D. C. Clary, A. A. Lewis, D. Morland, J. N. Murrell, and E. Heilbronner, *J. Chem. Soc., Faraday Trans. 2*, **70**, 1889 (1974).

(21) E. Heilbronner and J. P. Maier in "Electron Spectroscopy, Theory, Techniques and Applications", C. R. Brundle and A. D. Baker, Eds., Academic Press, London, 1977.

(22) M. Beez, G. Bieri, H. Bock, and E. Heilbronner, *Helv. Chim. Acta*, **56**, 1028 (1973).

(23) C. Batich, P. Bischof, and E. Heilbronner, *J. Electron Spectrosc.*, 1, 333 (1972).

(24) The Varian XL-100 NMR spectrometer was obtained with a major equipment grant from the National Science Foundation.

The He(Iα) photoelectron spectra of the hydrocarbons **1**, **2**, **4**, and **5** were recorded on a Turner-type instrument incorporating a $\pi/2$ cylindrical analyzer of 10-cm radius (Perkin-Elmer PS 16). The temperatures necessary to obtain sufficient sample vapor pressure were 45 °C for **4**, 90 °C for **2**, 65 °C for **1**, and 135 °C for **5**. The resolution was typically $\sim$150.

1-(1-Hydroxycyclobutyl)cyclopentene (12). Under nitrogen, 3.60 g (0.15 mol) of dry magnesium turnings and 5.0 mg of iodine were stirred in 15 mL of dry THF. Approximately 2.0 mL of a solution of 1-bromocyclopentene[25] (22.05 g, 0.15 mol) in 20 mL of dry THF was added to the reaction vessel. After the mixture was heated briefly, a mildly exothermic reaction began. The remaining vinyl halide solution was added dropwise, at a rate to control the exothermic reaction. The reaction mixture was refluxed 35 min after complete addition of the 1-bromocyclopentene solution and then cooled to room temperature. A solution of 9.10 g (0.13 mol) of cyclobutanone in 15 mL of dry THF was then added dropwise to the reaction mixture. At the conclusion of the mildly exothermic reaction, the reaction mixture was refluxed for 1.25 h, cooled to room temperature, and hydrolyzed by dropwise addition of 18.2 mL of saturated ammonium chloride solution. This mixture was stirred vigorously at room temperature for 30 min and suction filtered, and the solid precipitate was thoroughly washed with ether. The filtrate was dried over $MgSO_4$, and the solvent was removed through a 15-cm Vigreux column on a steam bath. Distillation of the residue provided 12.44 g (69%) of 1-(1-hydroxycyclobutyl)cyclopentene: bp 79–82 °C (3.5 mm); NMR (CCl_4) δ 5.55 (t, 1 H, J = 2.0 Hz), 3.7 (br s, shifts on dilution, 1 H) and 1.1–2.6 (m, 12 H); IR (thin film) 3550–3100, 3045, 2935, 2841, 1640, 1440, 1255, 1123, 1050, 943, 885, 810, 770 cm^{-1}.

1-(1-Cyclobutenyl)cyclopentene (6b). To 3.45 g (25 mmol) of allylic alcohol **12** was added 1.09 g (7.5 mmol) of potassium bisulfate, and the resulting suspension was stirred and heated to 120–125 °C in an oil bath. Vigorous boiling began, the reaction became exothermic, and heating was temporarily discontinued. After the reaction had subsided, the mixture was heated for an additional 15 min at 120–125 °C and then cooled to room temperature. The inorganic salts were dissolved by the addition of 1–2 mL of water, and the organic layer was separated and dried over potassium carbonate. Distillation provided 1.80 g (60%) of diene **6b**: bp 53 °C (7–8 mm); NMR (CCl_4) δ 5.66 (br s, 1 H), 5.50 (br s, 1 H), 1.5–2.7 (overlapping m, 10 H).

Dimethyl Tetracyclo[9.2.0.0^{2,6}.0^{7,10}]tridec-6(7)-ene-1,11-dicarboxylate (8b). In a base-washed, heavy-walled glass tube were placed 1.63 g (13.6 mmol) of 1-(1-cyclobutenyl)cyclopentene (**6b**), 2.30 g (13.6 mmol) of dimethyl 1,2-cyclobutenedicarboxylate (**7**),[26] and a 5 mg of hydroquinone. The tube was sealed and heated for 17 h at 125–135 °C. After cooling, the tube was opened and the crude product was immediately chromatographed on 100 g of silica gel, eluting with 30% ethyl ether/petroleum ether to provide 3.10 g (78%) of **8b** as a pale yellow oil: NMR ($CDCl_3$) δ 3.5–3.7 (2 overlapping s, 6 H), 1.1–3.0 (m, allylic and aliphatic H, 16 H); IR (thin film) 2948, 2870, 2840, 1740, 1446, 1250, 1140, 1115, 1090, 836 cm^{-1}.

Tetracyclo[9.2.0.0^{2,6}.0^{7,10}]tridec-6(7)-ene-1,11-dicarboxylic Acid (9b). To 2.90 g (10 mmol) of **8b** were added 50% aqueous KOH (3.36 g of KOH in 3.36 mL of H_2O) and 20 mL of methanol. The resulting mixture was refluxed for 24 h under nitrogen. After cooling, the reaction mixture was washed into a separatory funnel with saturated NaCl solution (75 mL), acidified with 12 M HCl, and extracted five times with ethyl ether. The organic layers were combined and dried over sodium sulfate, and the solvent was removed under reduced pressure to afford 2.06 g (79%) of the dicarboxylic acid **9b**:[27] mp 86–90 °C; NMR (Me_2SO-d_6) δ 9.1–9.2 (br, COOH, 2 H), 1.0–3.6 (m, allylic and aliphatic H, 16 H).

Dimethyl Tetracyclo[8.2.0.0^{2,5}.0^{6,9}]dodec-5(6)-ene-1,10-dicarboxylate (8c). In a base-washed, heavy-walled glass tube were placed 0.75 g (7.1 mmol) of 1,1′-bicyclobutenyl[11b,12] (**6c**) 1.2 g (7.1 mmol) of dimethyl-1,2-cyclobutenedicarboxylate (**7**),[26] and 10 mg of hydroquinone. The tube was sealed and heated to 110 °C for 12 h. After cooling, the tube was opened, and the crude product was washed out with carbon tetrachloride. Analysis by VPC (5 ft × 0.125 in. 1.5% OV-101 on Chromsorb G, 100/120 mesh, at 180 °C and 30 mL/min) showed two peaks at retention times of 7.0 (19%) and 9.2 (81%) min. It is presumed that these two peaks represent the endo and exo Diels–Alder adducts. Chromatography of the crude adduct on 70–230-mesh silica gel, eluting with 1:4 ether/hexane, gave 1.16 g (60%) of this mixture of epimers as a colorless oil which was separated into its two pure components by preparative gas chromatography. Major component: NMR ($CDCl_3$) δ 3.64 (s, 6 H, CO_2CH_3), 3.5–1.4 (m, 14 H); IR (thin film) 3000, 2960, 2910, 1740, 1730, 1438, 1260, 1250, 1225, 1120, 910, 730 cm^{-1}. Minor component: NMR ($CDCl_3$) δ 3.68 (s, 6 H, CO_2CH_3), 3.5–1.4 (m, 14 H): IR (thin film) 3000, 2960, 2920, 2890, 1740, 1730, 1450, 1440, 1335, 1280, 1230, 1220, 1200, 1150, 1130, 1110 cm^{-1}.

Tetracyclo[8.2.0.0^{2,5}.0^{6,9}]dodec-5(6)-ene-1,10-dicarboxylic Acid (9c). To a stirred solution of 1.1 g (4 mmol) of **8c** in 20 mL of methanol was added a solution of 1.8 g (32 mmol) of KOH in 3 mL of water. The mixture was refluxed for 20 h under nitrogen, cooled, poured into 100 mL of saturated NaCl solution and acidified with concentrated HCl. The aqueous solution was extracted five times with ether, and the combined ether extracts were dried over anhydrous sodium sulfate. The solution was filtered and the ether evaporated to provide 0.92 g (93%) of the dicarboxylic acid **9c**:[27] mp 163–168 °C; NMR (Me_2SO-d_6) δ 3.1 (m, 2 H), 2.58 (m, 4 H), 2.0 (m, 8 H); IR (KBr) 2950, 1715, 1100, 900 cm^{-1}.

1,2:3,4-Dicyclobuta[5,6]cyclopentabenzene (3). To a solution of 2.0 g (7.6 mmol) of dicarboxylic acid **9b** in 25 mL of dry Me_2SO and 2.42 g (30.6 mmol) of pyridine, under nitrogen, was added 6.77 g (15.3 mmol) of vacuum dried lead tetraacetate at a rate to keep the temperature below 40 °C. After being stirred for 30 min, the reaction mixture was poured into 150 mL of water and extracted four times with ethyl ether. The combined organic layers were dried over anhydrous magnesium sulfate and filtered. The solvent was removed under reduced presure and the oily residue was immediately chromatographed on 30 g of silica gel, eluting with hexane to afford 35 mg (3%) of hydrocarbon **3**: mp 89–90 °C; IR (KBr) 2961, 2928, 2918, 2850, 1492, 1470, 1386, 1248, 1215, 668 cm^{-1}; UV (95% ethanol) 261 nm (ϵ 317), 265 (364), 267 (378), 273 (310), 275 (250); NMR ($CDCl_3$) δ 3.12 (s, 8 H), 2.73 (t, 4 H, J = 7.2 Hz), 2.02 (quintet, 2 H, J = 7.2 Hz); mass spectrum (70 eV), m/e (relative intensity) 170 (100), 169 (26), 154 (32), 153 (46), 152 (23), 142 (28), 141 (61), 129 (34), 128 (62), 115 (67), 91 (24), 77 (21), 63 (20), 51 (24); calcd for $C_{13}H_{14}$ m/e 170.1095, found m/e 170.1099.

Tricyclobutabenzene (4). In a 25-mL, three-necked, round-bottomed flask equipped with a reflux condenser, a thermometer, and under nitrogen were placed 0.46 g (1.85 mmol) of dicarboxylic acid **9c**, 5 mL of dry Me_2SO and 0.3 g (3.8 mmol) of pyridine. The mixture was stirred until a homogeneous solution was obtained. To this solution was added 0.82 g (1.85 mmol) of vacuum dried lead tetraacetate in one portion. A slight exothermic reaction and the evolution of gas were observed. The reaction temperature was maintained at 25–40 °C. After the gas evolution had ceased (ca. 10 min), the mixture was poured into 35 mL of water, and the resulting aqueous solution was extracted six times with ether. The combined ether extracts were dried over anhydrous potassium carbonate, and the ether was removed on the rotary evaporator to give an oily residue which was passed through a short silica gel column eluted with hexane to give a light yellow liquid. This liquid was taken up in 5 mL of carbon tetrachloride and treated with 0.05 g of 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ). After being stirred at room temperature for 5 156.0939, found m/e 156.0932. was passed through a silica gel column eluted with hexane to give 10.8 mg (3.6%) of crystalline tricyclobutabenzene: mp 141–142 °C; NMR ($CDCl_3$) δ 3.12 (s, 12 H, cyclobutenyl H); GC mass spectrum, m/e (relative intensity) 156 (100.0, parent ion for $C_{12}H_{12}$), 141 (37.6, M – 15), 128 (19.0, M –28), 115 (25.9, M – 41); UV (isooctane) λ_{max} 269 (ϵ 170), 264 (sh, 190), 262 (210), 258 (195), 254 (195), 251 (sh, 170), 247 (sh, 150), 222 (5600), 201 (25 500); IR ($CHCl_3$) 2940, 2870, 1615, 1470, 1384, 1270, 1100 cm^{-1}; calcd for $C_{12}H_{12}$ m/e 156.0939, found m/e 156.0932.

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[25] P. Maitte, *Bull. Soc. Chim. Fr.*, 499 (1959).

[26] R. N. McDonald and R. R. Reitz, *J. Org. Chem.*, **37**, 2418 (1972).

[27] In some systems the dicarboxylic acids were found to undergo extremely facile dehydration to produce an anhydride, thus accounting for a depressed melting point and lack of a COOH proton signal in the NMR.

[28] Z. Z. Yang, E. Heilbronner, H. C. Kang, and V. Boekelheide, *Helv. Chim. Acta*, in press.

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Computer-Assisted Mechanistic Evaluation of Organic Reactions. 3. Ylide Chemistry and the Organometallic Chemistry of Lithium, Magnesium, and Lithium Cuprates[1]

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CAMEO, an interactive computer program for the mechanistic evaluation of organic reactions, has been enhanced to encompass ylide chemistry and organometallic reactions involving Li, Mg, and CuLi counterions. Based on literature precedents, alogrithms have been developed to handle the competitions between proton transfer, organometallic addition, and halogen–metal exchange. These processes yield the anionic nucleophiles which are considered for subsequent participation in E1cB, S_N2, E2, and addition reactions. Algorithms to treat the competitions between the latter processes were described previously and remained essentially unchanged. The major modifications for organometallic chemistry involved the routines for pK_a and nucleophile perception. CAMEO is now capable of making sophisticated predictions for a wide variety of synthetically useful base-catalyzed and/or nucleophilic reactions. Sample sequences and a pedagogic flow chart for making logical predictions on the outcomes of such reactions are provided.

I. Introduction

An overview of a new computer program, CAMEO, which predicts products of organic reactions when given starting materials and reaction conditions has recently been presented.[3] A key feature of the program is that it arrives at its predictions by using mechanistic reasoning and fundamental concepts concerning structure and reactivity. Furthermore, the program is interactive and easy to use since the input and output of commands and molecular structures are performed graphically via a computer graphics terminal. The first mechanistic class to be addressed was base-catalyzed and nucleophilic reactions which often involve a proton-transfer prestep. Relative basicities and other data are used to find the best nucleophiles and electrophiles which may subsequently participate in E1cB, E2, S_N2, and addition reactions. Heuristics based on literature precedents then enable evaluation of the competitions between these processes.

As described here, this work has been extended to cover reactions of organolithium, magnesium, and lithium cuprate reagents in which cases proton transfer may not be a valid first step. Instead, the competitions between organometallic addition, proton transfer, and halogen–metal exchange must be considered.[4,5] With relatively minor modifications it has been possible to incorporate the organometallic chemistry into the existing program. In addition, the complementary area of ylide chemistry has also been integrated at the same time. With these enhancements the program is now capable of making sophisticated predictions for most base-catalyzed and nucleophilic reactions which are of particular utility to synthetic organic chemists. Further extensions to electrophilic and pericyclic chemistry are in progress.

To begin, a brief review of reactions for organolithium, Grignard, and lithium cuprate reagents and ylides is provided. The apparent patterns are then organized into heuristics for use by CAMEO. This is followed by a description of the implementation of the new material in the program. A summary of the mechanistic logic used by CAMEO to predict reaction products is then presented with the aid of a pedagogically oriented flow chart. The paper concludes with examples of typical reaction sequences predicted by CAMEO.

The program as described here is now operating on a Harris Corporation H-80 computer equipped with a Tektronix 4010 terminal and electrostatic pen and tablet. This system replaced the original TI 990/10 computer and has significantly enhanced the ease of program development due to its much greater speed and larger word size. The program can now handle molecules with up to 46 explicit atoms and bonds and the response time between reactant input and product display has been reduced to several seconds in typical cases.

II. Review of Reactions

A. Preparation of Organometallic Reagents. The two reactions used in the preparation of organometallics which CAMEO is able to handle at this time are proton transfer and halogen–metal exchange. The former process is facile in many instances in which addition is not competitive. Thus, *N*-methylbenzamide may be metalated as

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(1) Taken in part from the Ph.D. thesis of T. D. Salatin, Purdue University, 1980. For part 2, see B. L. Roos-Kozel and W. L. Jorgensen, *J. Chem. Inf. Comp. Sci.*, 21, 101 (1981).

(2) Camille and Henry Dreyfus Foundation Teacher–Scholar 1978–1983; Alfred P. Sloan Foundation Fellow 1979–1981.

(3) T. D. Salatin and W. L. Jorgensen, *J. Org. Chem.*, 45, 2043 (1980).

(4) (a) B. J. Wakefield, "The Chemistry of Organolithium Compounds", Pergamon Press, Oxford, 1974; (b) For a general review of carbanion chemistry, see J. C. Stowell, "Carbanions in Organic Synthesis", Wiley, New York, 1979.

(5) M. S. Karasch and O. Reinmuth, "Grignard Reactions of Nonmetallic Substances", Prentice-Hall, New York, 1954; see also ref 4b.

0022-3263/81/1946-5284$01.25/0