(2*R*,5*R*)-**2** (>97% by ^{1}H NMR) was isolated by fractional crystallization of the bisulfate salts followed by release of the free base [21 g, 31% yield from menthone, $[\alpha]_D^{23} = +43.3°$ (*c* 2.5, $CHCl_3$)]. Thermolysis of (2*R*,5*R*)-**2** in the presence of KBH_4 (0.33 equiv, 1.5 h in dimethylacetamide, 6.5 h in anisole) yielded the desired ligand K[HB((2*R*,5*R*)-menthylpz)$_3$] [**3**; 46% based on (2*R*,5*R*)-**2**] contaminated by unreacted (2*R*,5*R*)-**2**. Isolation of pure **3** proved difficult, so the crude ligand was used directly to precipitate the complexes [HB((2*R*,5*R*)-menthylpz)$_3$]MCl [M = Zn (**6**) or Ni (**7**)] by adding the appropriate metal(II) halide in MeOH. Additional complexes [HB((2*R*,5*R*)-menthylpz)$_3$]MX [X = Cl, M = Cu (**8**) or Co (**9**); X = OAc, M = Cu (**10**) or Ni (**11**); X = NO_3, M = Cu (**12**) or Ni (**13**)] were prepared by metal exchange with **6** or by coligand metathesis reactions. We have also synthesized other potentially useful multidentate optically active ligands from (2*R*,5*R*)-**2**, including phospine oxide **4** (a neutral analog of **3**) and pyridine **5** (a C_2-symmetric meridianal binder).[11]

Similarities among the properties of the complexes of **3**[10] and those of known analogs containing hindered achiral tris(pyrazolyl)hydroborate ligands[4c,5a,12] support assignment of tetrahedral geometries to **7–9** and square pyramidal structures to **10–13**.[13] The absolute configuration of the ligand was obtained, and its tridentate C_3-symmetric coordination mode was confirmed by an X-ray crystal structure analysis of **6** (Figure 1).[14] The propellor of alternating isopropyl groups and hydrogen atoms fixed at the periphery of the metal-centered ligand cavity in **6** provides a unique and highly directed asymmetric environment which contrasts with the topology of complexes of previously reported camphorpyrazole ligands in which the alternating array of dimethylmethano and ethano moieties forms a torus well-removed from incoming substrates.[6,7a]

The practical synthesis of (2*R*,5*R*)-**2**, its elaboration into ligands **3–5**, and the isolation and characterization of a series of first-row transition metal complexes of **3** represent significant first steps in the development of a new class of chiral, C_3-symmetric catalysts and metal-centered templates for stereoselective molecular recognition. In view of the prevalence of tris(pyrazolyl)hydroborate complexes in the contemporary organometallic and inorganic chemical literature,[1-5] the recent successes in the use of optically active N-donor ligands in asymmetric synthesis,[15] and the ready accessibility and novel structural features of **3** (e.g., fixed, convergent, and highly sterically differentiated C_3 array of stereogenic centers), we believe that there exists a wide range of promising options for future enantioselective reactivity studies of its complexes.

Acknowledgment. We thank Professor Doyle Britton for his work on the X-ray structure of **6**, Bijan Mossadeghi for the initial synthesis of **5**, and Professor H. Brunner (Universität Regensburg) for a preprint and a copy of the Ph.D. thesis of T. Scheck. Funding for this research was provided by the Petroleum Research Fund, administered by the American Chemical Society, the National Science Foundation (Grant CHE-9207152), the University of Minnesota's Undergraduate Research Opportunities Program (D.D.L.), and the University of Minnesota.

Supplementary Material Available: Preparative procedures and analytical and spectroscopic data for **2-13** and fully labeled ORTEP drawing, fractional coordinates, bond distances, bond angles, and anisotropic thermal parameters for **6** (24 pages); observed and calculated structure factor amplitudes for the X-ray structure of **6** (27 pages). Ordering information is given on any current masthead page.

---

(10) Synthetic procedures and analytical and spectroscopic data for all new compounds are reported in the supplementary material.

(11) Camphorpyrazole analogs of **5**: Watson, A. A.; House, D. A.; Steel, P. J. *J. Org. Chem.* **1991**, *56*, 4072–4074.

(12) (a) Gorrell, I. B.; Parkin, G. *Inorg. Chem.* **1990**, *29*, 2452–2456. (b) Han, R.; Parkin, G. *J. Am. Chem. Soc.* **1991**, *113*, 9707–9708. (c) Kitajima, N.; Fujisawa, K.; Moro-oka, Y. *J. Am. Chem. Soc.* **1990**, *112*, 3210–3212.

(13) A preliminary X-ray structure analysis of **11** confirmed assignment of a square pyramidal geometry to the complex (see supplementary material).

(14) X-ray data for **6** $C_{33}H_{52}N_6BZnCl$, *MW* 644.46, space group $P2_12_12_1$ (No. 19) at −101 °C: $a = 9.658(7)$ Å, $b = 17.777(7)$ Å, $c = 20.058(6)$ Å, $V = 3444(5)$ Å^3, $Z = 4$. For 4055 unique, observed reflections with $I > 2\sigma(I)$ (including Friedel pairs collected to $\theta = 20°$) and 379 variable parameters $R = 0.063$ and $R_w = 0.049$. Refinement using the opposite enantiomer converged to $R = 0.073$ and $R_w = 0.061$. Full tables of positional and thermal parameters, bond lengths and angles, and observed and calculated structure factor amplitudes are reported in supplementary material.

(15) (a) Bolm, C.; Ewald, M.; Felder, M.; Schlingloff, G. *Chem. Ber.* **1992**, *125*, 1169–1190, and references therein. (b) Bolm, C.; Schlingloff, G.; Harms, K. *Chem. Ber.* **1992**, *125*, 1191–1203. (c) Bolm, C.; Ewald, M.; Felder, M. *Chem. Ber.* **1992**, *125*, 1205–1215. (d) Evans, D. A.; Woerpel, K. A.; Hinman, M. M.; Faul, M. M. *J. Am. Chem. Soc.* **1991**, *113*, 726–728. (e) Corey, E. J.; Imai, N.; Zhang, H.-Y. *J. Am. Chem. Soc.* **1991**, *113*, 728–729. (f) Nishiyama, H.; Sakaguchi, H.; Nakamura, T.; Horihata, M.; Kondo, M.; Itoh, K. *Organometallics* **1989**, *8*, 846–848. (g) Nishiyama, H.; Kondo, M.; Nakamura, T.; Itoh, K. *Organometallics* **1991**, *10*, 500–508. (h) Fritschi, H.; Leutenegger, U.; Pfaltz, A. *Helv. Chim. Acta* **1988**, *71*, 1553–1565. (i) Fritschi, H.; Leutenegger, U.; Siegmann, K.; Pfaltz, A.; Keller, W.; Kratky, C. *Helv. Chim. Acta* **1988**, *71*, 1541–1552. (j) Matt, P. v.; Pfaltz, A. *Tetrahedron: Asymmetry* **1991**, *2*, 691–700. (k) Leutenegger, U.; Umbricht, G.; Fahrni, C.; Matt, P. v.; Pfaltz, A. *Tetrahedron* **1992**, *48*, 2143–2156. (l) Lowenthal, R. E.; Masamune, S. *Tetrahedron Lett.* **1991**, *32*, 7373–7376. (m) Ahn, K.-H.; Klassen, R. B.; Lippard, S. J. *Organometallics* **1990**, *9*, 3178–3181.

A [W(CO)$_5$·THF]-Mediated Pauson–Khand Reaction: Cyclizations of 1,6-Enynes via a Batch-Catalytic Protocol

Thomas R. Hoye* and Joseph A. Suriano

Department of Chemistry, University of Minnesota
Minneapolis, Minnesota 55455

Received October 13, 1992

The Pauson–Khand cyclization reaction (PKCR) merges alkyne, alkene, and carbon monoxide subunits into a common cyclopentenone ring.[1] The most widely used source of CO for these reactions is (a stoichiometric quantity of) dicobalt octacarbonyl. The only other reported metal carbonyl precursor to effectively cyclize enynes is $Fe(CO)_5$.[2] As part of our study of cyclization reactions of enynes with various Fischer carbene species, we observed the unexpected formation of the bicyclic cyclopentenone **2a** as a minor byproduct from reaction of 1,6-enyne **1a** with a tungsten-containing Fischer carbene [$(CO)_5W{=}CMe(OMe)$]. We speculated and then demonstrated that tungsten pentacarbonyl was the likely species which mediated that particular reaction.[3] This observation was unprecedented and of sufficient interest that we have studied and now report various aspects including the batch-catalytic nature of this new method of cyclopentenone synthesis.

Enynes **1a–j** were treated with preformed $W(CO)_5$·THF in a THF solution at 65–110 °C for 6–20 h to provide the bicyclo[3.3.0]octenones **2a–j** in the yields stated in Table I. The "parent" allyl propargyl malonate and *gem*-dimethylated substrates **1a** and **1b** cyclize smoothly when reacted with $W(CO)_5$·THF (W-PKCR), producing cyclopentenones **2a** and **2b**.[4] Minor byproducts of reductive cyclization and/or alkyne reduction, presumably via tungsten hydride containing intermediates, were always observed

---

(1) For the initial report, see: (a) Khand, I. U.; Knox, G. R.; Pauson, P. L.; Watts, W. E.; Foreman, M. I. *J. Chem. Soc., Perkin Trans. 1* **1973**, 977. For general reviews, see: (b) Pauson, P. L. In *Organometallics in Organic Synthesis. Aspects of a Modern Interdisciplinary Field*; de Meijere, A., tom Dieck, H., Eds.; Springer: Berlin, 1987; p 233. (c) Pauson, P. L. *Tetrahedron* **1985**, *41*, 5855. (d) Pauson, P. L.; Khand, I. U. *Ann. N. Y. Acad. Sci.* **1977**, *295*, 2. (e) Schore, N. E. *Chem. Rev.* **1988**, *88*, 1081. (f) Schore, N. E. *Org. React.* **1991**, *40*, 1–90. (g) Schore, N. E. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon: Oxford, 1991; Vol. 5, p 1037.

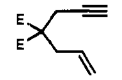
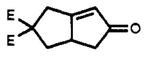
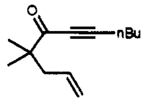
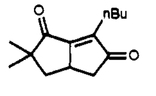
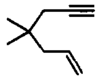
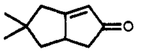
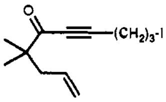
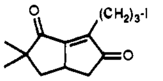
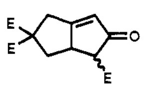
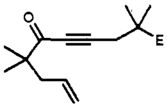
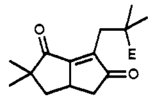
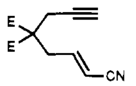
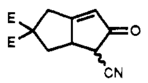
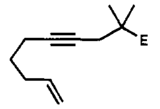
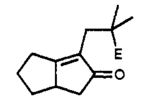
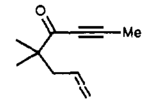
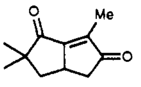
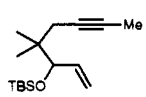
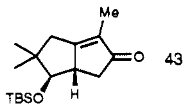
(2) Pearson, A. J.; Dubbert, R. A. *J. Chem. Soc., Chem. Commun.* **1991**, 202.

(3) Hoye, T. R.; Suriano, J. A. *Organometallics* **1992**, *11*, 2044.

(4) An intermediate in the total synthesis of pentalenene: Hua, D. H. *J. Am. Chem. Soc.* **1986**, *108*, 3835.

0002-7863/93/1515-1154$04.00/0

Table I. Reaction[a] of Pentacarbonyltungsten·THF with Enynes **1** To Produce Cyclopentenones **2**

Entry	Enyne *1*		Product *2*		yield, %[b]	Entry	Enyne *1*		Product *2*		yield, %[b]
a	*1a*		*2a*		60[c]	f	*1f*		*2f*		57
b	*1b*		*2b*		69[c]	g	*1g*		*2g*		51
c	*1c*		*2c*		21[c,d]	h	*1h*		*2h*		55
d	*1d*		*2d*		57[c]	i	*1i*		*2i*		17
e	*1e*		*2e*		71	j	*1j*		*2j*		43[e]

[a] In a typical experiment, a slurry of $W(CO)_6$ (176 mg, 0.50 mmol) in dry THF (10 mL) under argon and in a screw-capped 50-mL culture tube was irradiated for 2 h with 350-nm bulbs in a Rayonet reactor [Wrighton, M. *Chem. Rev.* **1974**, *74*, 401]. To the resulting bright yellow solution was added the enyne substrate **1** (0.45 mmol in ≤1 mL of THF). This solution was heated at external bath temperatures ranging from 65 to 110 °C from 6 to 20 h, during which time the color of the solutions typically turned through orange to red to brown to black. Carbon monoxide was slowly bubbled through the cooled solution for 1 h. Removal of the THF under reduced pressure, reconstitution of the residue in hexane/ethyl acetate, and filtration of the slurry allowed recovery of the majority of the initial quantity of $W(CO)_6$. Filtrate concentration and MPLC on SiO_2 returned an additional quantity of $W(CO)_6$ (total recovery of ~95%) and the enyne-derived product(s). [b] Yields are for material after purification by MPLC on silica gel. [c] Reduction byproducts[3] are methylenecyclopentenes (6–10%) and/or 1,6-dienes (2–3%, from simple alkyne reduction). [d] Plus 19% of **2a**. [e] Major diastereomer shown (3:1 β:α ratio as determined by ^{1}H NMR and capillary GC analyses).

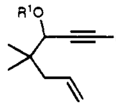
with substrates containing terminal alkyne C–H bonds.

Electron-deficient alkenes are often poor substrates for the $Co_2(CO)_8$-mediated reaction (Co-PKCR).[5] Although enoate **1c** gave α-carbomethoxy enone **2c** in only 21% yield under W-PKCR conditions, competing decarbalkoxylation of the product (**2a** was also isolated in 19%) and formation of reduced byproducts (Table I, footnote c) may be more responsible than any inherent lack of reactivity of the alkene in **1c**. This is supported by the smooth cyclization of the electron-deficient α,β-unsaturated nitrile **1d** to the keto nitrile **2d**.

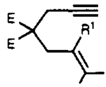
Electron-deficient alkynes are also poor substrates in standard Co-PKCRs.[1c,6] It is, therefore, interesting that the alkynones **1e–h**, bearing pendant vinyl groups, were well-behaved in W-PKCRs and gave access to the multifunctional enediones **2e–h**. For substrate **1e** the cyclization culminates a four-step construction of **2e**, an important intermediate in the Danishefsky coriolin synthesis.[7] We have recently observed that these electron-poor alkynone substrates are also quite efficiently cyclized by $Co_2(CO)_8$ in acetonitrile.[8]

The benefit of the *gem*-dialkyl effect[9] on the efficiency of this transformation is evidenced by the poor yield for cyclization of substrate **1i**. A class of successful substrates for the Co-PKCR is the propargylic ether containing enynes such as **1k–m**. Surprisingly, W-PKCR of these gave less than 5% of the corresponding cyclopentenones even under forcing conditions where all of the enyne substrate was consumed. On the other hand, enyne **1j**, containing the allylic ether subunit, was a moderately good substrate. The degree of diastereoselectivity observed in the $W(CO)_5$·THF cyclization of the allylic ether containing precursor **1j** (3:1) was very similar to that seen for the $Co_2(CO)_8$ cyclization of an analogous substrate (2.6:1, 25%).[10] Attempts to cyclize enynes **1n–p**, containing a second alkyl substituent on the alkene atoms, were not successful with the W-PKCR; however, they are well-behaved substrates in the Co-PKCR.

	R^1	R^2
1k	Me	H
1l	Me	Me
1m	TBS	Me



	R^1	R^2	R^3
1n	Me	H	H
1o	H	Me	H
1p	H	H	Me



The fact that $W(CO)_6$, an air-stable, easily handled, relatively safe metal carbonyl, can be routinely recovered in ~95% yield after exposure of the reaction mixture to an atmosphere of CO means that this process is batch-catalytic with regard to the metal species. Interestingly, the use of ~10 mol % $W(CO)_5$·THF in the presence of 1.0 equiv of added $W(CO)_6$ allowed the conversion of **1a** into **2a** in 45% yield, wherein the $W(CO)_6$ presumably served as the CO source.[11] Attempts to make the reaction truly catalytic through the use of substoichiometric amounts of $W(CO)_5$·THF in the presence of CO have been only marginally successful.

In conclusion, tungsten pentacarbonyl has been shown to promote Pauson–Khand-like cyclizations of a variety of substrates, including those containing electron-deficient alkene or electron-deficient alkyne moieties. Thus, $W(CO)_6$ should be considered

---

(5) (a) Khand, I. U.; Pauson, P. L. *J. Chem. Soc., Chem. Commun.* **1974**, 379. (b) Khand, I. U.; Pauson, P. L. *Heterocycles* **1978**, *11*, 59. (c) For a protocol for successful cyclization of electron-deficient alkenes, see: Veretenov, A. L.; Smit, W. A.; Vorontsova, L. G.; Kurella, M. G.; Caple, R.; Gybin, A. S. *Tetrahedron Lett.* **1991**, *32*, 2109.

(6) (a) Jaffer, H. J. Ph.D. Thesis, Strathclyde University, Glasgow, Scotland, 1982. (b) For an NMO-promoted protocol for successful cyclization of electron-deficient alkynoates, see: Krafft, M. E.; Romero, R. H.; Scott, I. L. *Abstracts of Papers*, 204th National Meeting of the American Chemical Society, Washington, DC, Fall 1992; American Chemical Society: Washington, DC, 1992; ORGN 256. Krafft, M. E.; Romero, R. H.; Scott, I. L. *J. Org. Chem.* **1992**, *57*, 5277.

(7) Danishefsky, S.; Zamboni, R.; Kahn, M.; Etheredge, S. J. *J. Am. Chem. Soc.* **1980**, *102*, 2097.

(8) Hoye, T. R.; Suriano, J. A. Manuscript in preparation.

(9) (a) de Tar, D. F.; Luthra, N. P. *J. Am. Chem. Soc.* **1980**, *102*, 4505. (b) Jung, M. E. *Synlett* **1990**, 186.

(10) Magnus, P.; Principe, L. M. *Tetrahedron Lett.* **1985**, *26*, 4851.

(11) The only examples of use of catalytic quantities of $Co_2(CO)_8$ of which we are aware result in turnover numbers of less than 10 and significantly less than 50% conversion of substrate(s): (a) Billington, D. C. *Tetrahedron Lett.* **1983**, *24*, 2905. (b) Magnus, P.; Principe, L. M.; Slater, M. J. *J. Org. Chem.* **1987**, *52*, 1483. (c) Billington, D. C.; Kerr, W. J.; Pauson, P. L.; Farnocchi, C. F. *J. Organomet. Chem.* **1988**, *356*, 213. (d) Rautenstrauch, V.; Megard, P.; Conesa, J.; Kuster, W. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 1413.

as a viable alternative to $Co_2(CO)_8$ for the synthesis of bicyclic cyclopentenones.

Acknowledgment. This investigation was supported by Grants GM-38854 and GM-34492 awarded by the DHHS. J.A.S. thanks the BASF Corporation and the University of Minnesota Graduate School for fellowship support.

Supplementary Material Available: Listings of ^1H and ^{13}C NMR, IR, MS, and elemental composition data for all new compounds (4 pages). Ordering information is available on any current masthead page.

More than INEPT: Parahydrogen and INEPT+ Give Unprecedented Resonance Enhancement to ^{13}C by Direct ^1H Polarization Transfer

Simon B. Duckett, Connie L. Newell, and
Richard Eisenberg*

Department of Chemistry
University of Rochester
Rochester, New York 14627

Received July 27, 1992

Enhanced absorptions and emissions in product NMR spectra have been reported to occur when H_2 oxidative addition and homogeneously catalyzed hydrogenation reactions are carried out using H_2 enriched in the para spin state.[1-10] The basis of this phenomenon, described initially by Weitekamp as PASADENA,[1,2] is that the addition of H_2 to substrate or metal complex takes place in a pairwise manner while spin correlation between the added protons is maintained. Termed parahydrogen-induced polarization (PHIP),[3] this phenomenon has been used to examine hydrogenation reaction mechanisms[5-7] and in one study to determine hydrogenation rate constants.[9] PHIP also transfers polarization from ^1H to ^{31}P and ^{13}C by cross-relaxation.[11] We now describe how these effects can be transferred to other nuclei through application of a pulse sequence to give extraordinary signal enhancements, thereby making it possible to rapidly observe naturally abundant ^{13}C resonances from small samples.

The reaction chemistry employed in the present study is the well-known oxidative addition of H_2 to $IrCl(CO)(PPh_3)_2$[12] and $IrBr(CO)(dppe)$[13] (dppe = bis(diphenylphosphino)ethane), which proceeds in a concerted way.[14-16] Utilization of *para-enriched* hydrogen (p-H_2)[17] yields polarized hydride resonances upon placement of the sample into the NMR probe immediately after thawing from 77 K and shaking to dissolve p-H_2.[2,4,11] In addition to normal J_{PH} couplings, the hydride resonances in these systems all show antiphase doublets corresponding to transitions that differ by J_{HH}. The antiphase character of these product resonances indicates overpopulation of the $\alpha\beta$ and $\beta\alpha$ proton spin states

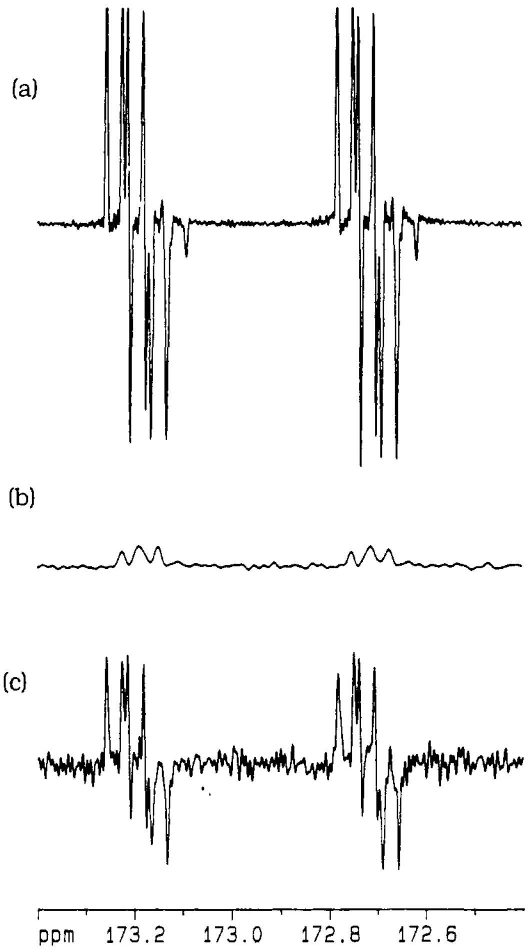


Figure 1. ^{13}C NMR spectra of $IrH_2Br(^{13}CO)dppe$ obtained using the INEPT+ pulse sequence: (a) spectrum from the reaction of 3 mg of $IrBr(^{13}CO)dppe$ with p-H_2 after 32 scans; (b) spectrum from the reaction of 3 mg of $IrBr(^{13}CO)dppe$ with n-H_2 after 256 scans; (c) spectrum from the reaction of 0.3 mg of IrBr(CO)dppe with p-H_2 after 32 scans with the ^{13}CO label present in natural abundance.

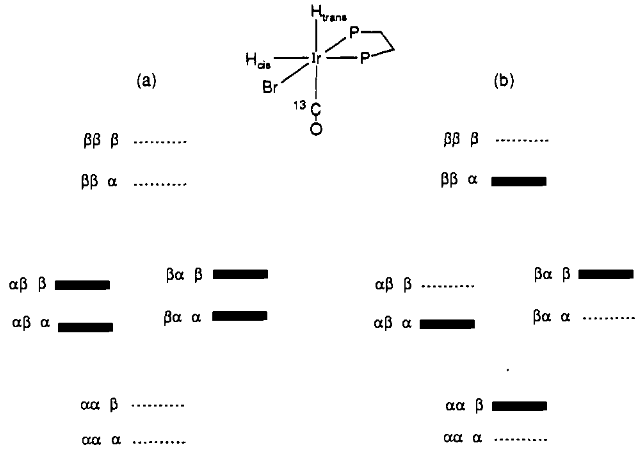


Figure 2. (a) Idealized representation of the initial populations of the energy levels for an AMX spin system produced from reaction with p-H_2, in which the spin function labels $\alpha\alpha\alpha$ etc. refer to H_{trans}, H_{cis}, and ^{13}C nuclei, respectively. (b) After execution of the INEPT+ pulse sequence, the energy level populations have been rearranged to yield non-Boltzmann distributions across the ^{13}C transitions.

---

(1) Bowers, C. R.; Weitekamp, D. P. *Phys. Rev. Lett.* **1986**, *57*, 2645-2648.

(2) Bowers, C. R.; Weitekamp, D. P. *J. Am. Chem. Soc.* **1987**, *109*, 5541-5542.

(3) Eisenschmid, T. C.; Kirss, R. U.; Deutsch, P. D.; Hommeltoft, S. I.; Eisenberg, R.; Bargon, J.; Lawler, R. G.; Balch, A. L. *J. Am. Chem. Soc.* **1987**, *109*, 8089-8091.

(4) Pravica, M. G.; Weitekamp, D. P. *Chem. Phys. Lett.* **1988**, *145*, 255-258.

(5) Kirss, R. U.; Eisenschmid, T. C.; Eisenberg, R. *J. Am. Chem. Soc.* **1988**, *110*, 8564-8566.

(6) Kirss, R. U.; Eisenberg, R. *J. Organomet. Chem.* **1989**, *359*, C22-C26.

(7) Eisenberg, R.; Eisenschmid, T. C.; Chinn, M. S.; Kirss, R. U. *Adv. Chem. Ser.*, in press.

(8) Eisenberg, R. *Acc. Chem. Res.* **1991**, *24*, 110.

(9) Chinn, M. S.; Eisenberg, R. *J. Am. Chem. Soc.* **1992**, *114*, 1908.

(10) Bargon, J.; Kandels, J.; Kating, P.; Thomas, A.; Woelk, K. *Tetrahedron Lett.* **1990**, *31*, 5721-5724.

(11) Eisenschmid, T. C.; McDonald, J.; Eisenberg, R.; Lawler, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 7267.

(12) Vaska, L.; DiLuzio, J. W. *J. Am. Chem. Soc.* **1962**, *84*, 679.

(13) Johnson, C. E.; Fisher, B. J.; Eisenberg, R. *J. Am. Chem. Soc.* **1983**, *105*, 7772.

(14) Vaska, L.; Werneke, M. F. *Trans. N.Y. Acad. Sci.* **1971**, *33*, 80.

(15) Tadros, M. E.; Vaska, L. *J. Colloid Interface Sci.* **1982**, *85*, 389.

(16) Johnson, C. E.; Eisenberg, R. *J. Am. Chem. Soc.* **1985**, *107*, 3148.

(17) Hydrogen was enriched to ca. 50 mol % parahydrogen by immersion of a 1-L flask containing iron(III) oxide on silica in liquid N_2 up to its neck. H_2 was added while 730-mm ambient hydrogen pressure was maintained. In this manner ~3-4 atm of p-H_2 at ambient temperature was produced.

0002-7863/93/1515-1156$04.00/0 © 1993 American Chemical Society