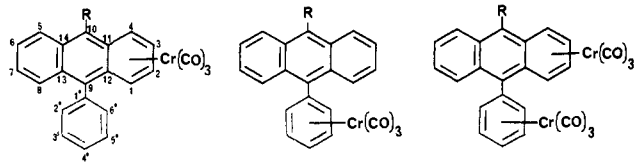
Chart I



Ia, R = H
Ib, R = Ph

IIa, R = H
IIb, R = Ph

IIIa, R = H
IIIb, R = Ph

Use of di-*n*-butyl ether as solvent again produced a purple solution, which after 7 h of reflux (approximately 75% reaction by CO gas evolution) was quickly cooled; chromatography on silica gel under pressure (ca. 2 bar) at 3 °C (eluents: pentane, pentane–ether (2:1), and ether) yielded three fractions (weights ca. 5:5:1, overall yield 30–35%), which were purple, yellow, and purple respectively. The yellow fraction was shown to be IIa. The two purple fractions have structures Ia[6] and IIIa,[7] respectively. Complex IIIa is extremely labile, and satisfactory solution spectra were not obtained; oxidation or heat changes IIIa to IIa.

For Ia, the upfield shift in the ^1H NMR spectrum of signals δ 6.58–5.73 (4 H) and in the ^{13}C NMR of six signals (δ 105.7–89.3) indicates binding of the $Cr(CO)_3$ group to a terminal ring of the anthracene portion of the molecule. Carbonyl bands at 1960, 1899, and 1882 cm^{-1} (Et_2O) are comparable to those of ATC (1982, 1924, and 1897 cm^{-1} in cyclohexane[3]). The visible–UV spectrum shows a maximum at 514 nm (cf. 512 nm for ATC). For the free ligand, the aromatic absorptions (300–400 nm) contain at least five distinct bands, whereas only a single very broad band appears for complex Ia.

The signal at δ 5.75 (5 H) in the ^1H NMR spectrum of IIa indicates binding of the $Cr(CO)_3$ group to the external ring of the ligand (confirmed by four signals (δ 108.6–90.7) in the ^{13}C NMR spectrum). The signal at δ 9.45 is assigned to H(1) (or H(8)), which is deshielded by the $Cr(CO)_3$ group. This signal disappears on heating (dioxane-d_8) to 99 °C and reappears on cooling to ca. 80 °C. The signals at δ 5.75 are unchanged; this indicates that at 99 °C, the $Cr(CO)_3$ group is still bound to the external phenyl ring and that the changes observed at higher temperatures in the downfield region must be attributed to increased oscillation or rotation of the external phenyl ring about the C(9)–C(1′) bond. That there are more than eight signals in the normal aromatic region of the ^{13}C NMR spectrum also suggests restricted rotation about the C(1′)–C(9) bond. The visible–UV spectrum shows a band at ca. 433 nm, which appears as a shoulder on the aromatic absorptions in the 300–400-nm range.

The formation of Ia from IIa also occurs in *n*-Bu_2O. A boiling solution of IIa in *n*-Bu_2O changed over 6 h from yellow to dark purple. Quick cooling of this solution and chromatography yielded both Ia and IIa. Differential scanning calorimetry of IIa reveals first an exothermic irreversible process (probably a crystal modification) at 165–170 °C. Melting occurs at 215 °C, accompanied by endothermic conversion of IIa to Ia. At 223 °C exothermic decomposition occurs; thermogravimetric measurements indicate loss of three molecules of CO. In contrast, crystalline Ia undergoes decomposition at ca. 80 °C, with no evidence for formation of IIa. The equilibrium constant for the reaction IIa $\rightleftarrows$ Ia in molten 9-phenylanthracene has been determined. A mixture of IIa and ligand (mole ratio ca. 1:5.7) gave K_{eq} values of 1.37 ± 0.03 at 490 K and 1.25 ± 0.03 at 470 K; thus, ΔH = 9.0 ± 4.0 kJ/mol for the migration process.

The 9,10-diphenylanthracene system has also been studied. Compounds Ib, IIb, IIIb, and a bis(tricarbonyl)chromium complex in which the two $Cr(CO)_3$ groups are on the external rings have been isolated and characterized. Migration of the $Cr(CO)_3$ group transforming IIb to Ib has also been observed.

Further studies of the equilibria described are in progress, as are kinetic studies to elucidate the mechanism of $Cr(CO)_3$ group migration. It is probable that this migration is intermolecular,[8] as an intramolecular process seems unlikely on steric grounds.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of the work carried out at Bucknell University. B.R.W. thanks the Fulbright Kommission, Bonn, for a travel grant and the Deutscher Akademischer Austauschdienst for financial support. We thank Victor Amato for preliminary experiments and Professor Frank Köhler for helpful discussions.

Registry No. Ia, 85629-62-5; Ib, 85629-63-6; IIa, 85629-64-7; IIb, 85629-65-8; IIIa, 85629-66-9; IIIb, 85629-67-0.

(6) Anal. Calcd for $C_{23}H_{14}CrO_3$: C, 70.77; H, 3.61; Cr, 13.32. Found: C, 70.48; H, 3.68; Cr, 13.30. Mass spectrum, *m/z* 390 (M^+), 362 [(M – CO)$^+$], 334 [(M – 2CO)$^+$], 306 [(M – 3CO)$^+$], 254 [(M – Cr – 3CO)$^+$], 52 (Cr^+); ^1H NMR (60 MHz, CD_2Cl_2) δ 9.45 (m, 1 H), 8.65 (s, 1 H), 8.1 and 7.6 (m, 7 H), 5.75 (m, 5 H); ^{13}C NMR (50.31 MHz, CD_2Cl_2) δ 131.8, 131.0, 130.8, 129.0, 128.5, 128.1, 127.9, 126.1, 125.3, 125.0, 124.6, 108.6 (Cl′), 99.0 (C3′, C5′), 93.5 (C4′), 90.7 (C2′, C6′); IR (Et_2O) 1969, 1900 cm^{-1}.

(7) Mass spectrum (field desorption ionization), *m/z* 526 (M^+), 470 [(M – 2CO)$^+$], 442 [(M – 3CO)$^+$], 390 [(M – Cr – 3CO)$^+$], 358 [(M – 6 CO)$^+$], 334 [(M – Cr – 5CO)$^+$], 306 [(M – Cr – 6CO)$^+$], 254 [(M – 2Cr – 6CO)$^+$], 52 (Cr^+).

(8) Mahaffy, C. A. L.; Pauson, P. L. *J. Chem. Res., Synop.* **1979**, 126–127; *J. Chem. Res., Miniprint* **1979**, 1752–1775. Zimmerman, C. L.; Shaner, S. L.; Roth, S. A.; Willeford, B. R. *ibid.* **1980**, (S)108, (M)1289–1297.

Stereochemistry of Hydroboration of α-Chiral Olefins and Reduction of α-Chiral Ketones. An Unusual Anti-Cram Selectivity with Dialkylboranes

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Prediction of the relative asymmetric induction for addition to chiral carbonyl compounds has been a subject of great interest from a synthetic and mechanistic point of view.[1] A variety of transition-state models based on steric approach control have been proposed for nucleophilic additions to chiral carbonyl compounds.[2] Although derived from different concepts, each model predicts the Cram product unless other factors such as metal chelation of the carbonyl group with a nearby oxygen or nitrogen are involved. However, we have discovered that different stereochemical pathways are involved in the reduction of chiral ketones with nucleophilic organoborohydrides and electrophilic organoboranes. As a result, either Cram or anti-Cram product can be predominantly produced. In a similar manner, hydroboration of the methylene compound derived from the ketone proceeds in a highly anti-Cram fashion. These results allow one to effectively control stereochemistry in an acyclic system.

During the investigation of the synthesis of steroid side chains,[3] we required an authentic mixture of a 22-hydroxy steroid epimeric at C-20. The mixture could be prepared by hydroboration of a 20(22)-methylene steroid. Since there was a discrepancy in the literature about the stereochemistry of such hydroborations,[4] we

(1) For a general review see: Morrison, J. D.; Mosher, H. S. "Asymmetric Organic Reactions"; Prentice-Hall: New York, 1971; reprinted American Chemical Society: Washington, D.C., 1976. Bartlett, P. A. *Tetrahedron* **1980**, *36*, 2.

(2) (a) Cram, D. J.; Abd Elhafez, F. A. *J. Am. Chem. Soc.* **1952**, *74*, 5828. (b) Cram, D. J.; Wilson, D. R. *Ibid.* **1963**, *85*, 1245. (c) Cornforth, J. W.; Cornforth, R. H.; Mathew, K. K. *J. Chem. Soc.* **1959**, 112. (d) Karabatsos, G. J. *J. Am. Chem. Soc.* **1967**, *89*, 1367. (e) Cherest, M.; Felkin, H.; Prudent, N. *Tetrahedron Lett.* **1968**, 2199. (f) Anh, N. T.; Eisenstein, O.; Lefour, J. M.; Tran Huu Dau, M. E. *J. Am. Chem. Soc.* **1973**, *95*, 6146. (g) Anh, N. T.; Eisenstein, O. *Nouv. J. Chim.* **1977**, *1*, 61. (h) Arjona, O.; Perez-Ossorio, R.; Perez-Rubalcaba, A.; Quiroga, L. *J. Chem. Soc., Perkin Trans. 2* **1981**, 597.

(3) Midland, M. M.; Kwon, Y. C. *J. Org. Chem.* **1981**, *46*, 229. Midland, M. M.; Kwon, Y. C. *Tetrahedron Lett.* **1982**, *23*, 2077.

(4) Bottin, J.; Fetizon, M. *J. Chem. Soc., Chem. Commun.* **1971**, 1087. Bottin, J.; Fetizon, M. *Bull. Soc. Chim. Fr.* **1972**, 2344. Byon, C.; Buyuktur, G.; Choay, P.; Gut, M. J. *Org. Chem.* **1977**, *42*, 3619.

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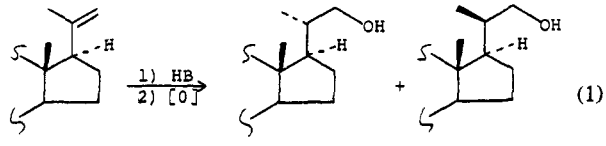
Table I. Stereochemistry of Additions to 1 and 4[a]

reducing agent	2:3[b]	5:6[c]	reducing agent	5:6[d]
BMS	1:1	1:6.3	$NaBH_4$	1:5
thexylborane	4:1		$LiAlH_4$	1:3
9-BBN	14:1	1:1.2	$LiEt_3BH$	1:20
disiamylborane	22:1	10:1[e]	K-*s*-Bu_3BH	1:9
dicyclohexylborane	26:1	9:1[f]	Li-*s*-Bu_3BH	1:54 (1:105)
bis(*trans*-2-methylcyclohexyl)borane	54:1	10:1[g]	NB-Enantride	(1:83)

[a] Chemical yields (NMR) are generally greater than 90%. [b] Isomeric ratio by HPLC. Hydroborations were conducted at 0 °C with 1 equiv of dialkylborane. [c] Isomeric ratio by HPLC. Reductions were conducted at 0 °C except as noted, by using 4 equiv of dialkylborane, overnight. [d] Isomeric ratio by HPLC. Reductions were conducted at 25 °C (or −78 °C in parentheses) by using 2 equiv of reducing agent. [e] 38% complete after 17 h. [f] 100% complete after 17 h at 25 °C. [g] 13% complete after 40 h.

decided to investigate the reaction in more detail. We found that hydroboration occurs predominantly from the top (*si*) face as depicted in eq 1 to provide the 20*S* product.[5] Indeed, with a



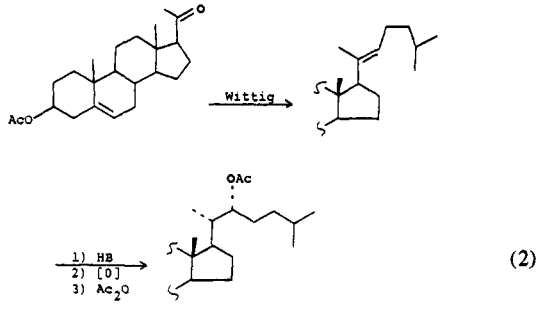
(1)

20S 20R

1 2 3

hindered borane such as bis(*trans*-2-methylcyclohexyl)borane, a greater than 98% epimeric purity may be obtained (Table I). In a ketone system such a stereochemical outcome would represent an anti-Cram addition!

The results are very useful since the (20*S*)-22-hydroxy steroid contains the correct natural configuration at C-20 and may be elaborated to more complex side chains.[3] The reaction may also be extended to a trisubstituted olefin. Pregnenolone is readily converted into an *E*-trisubstituted olefin by the Wittig reaction (eq 2).[6] Hydroboration with 9-borabicyclo[3.3.1]nonane (9-BBN)



(2)

proceeds in a highly chemoselective and stereoselective manner. Although the acetate is reduced, the 5(6) double bond remains intact. The 20*S*,22*R* isomer is essentially the only product (20*S*,22*R*:20*R*,22*S* = 300:1 by HPLC). This process represents one of the simplest methods for obtaining the stereochemistry found in the insect molting hormone ecdysone.[7,8]

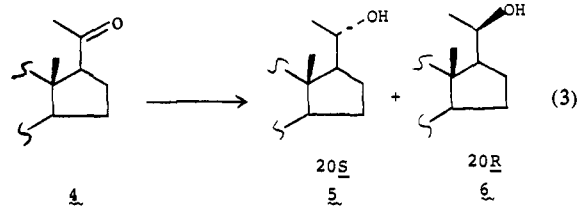
(5) The product was analyzed by HPLC and compared to authentic samples of the 20*S* alcohol or the corresponding (20*R*)- and (20*S*)-22-cyano compounds.[3]

(6) Schow, S. R.; McMorris, T. C. *J. Org. Chem.* **1979**, *44*, 3760. For an assignment of the stereochemistry see: Anderson, W. G., Byon, C. Y.; Gut, M.; Bissett, F. H. *Tetrahedron Lett.* **1976**, 2193.

(7) Lee, E.; Lue, Y.-T.; Solomon, P. H.; Nakanishi, K. *J. Am. Chem. Soc.* **1976**, *98*, 1634.

(8) Hydroboration of the *Z* isomer (obtained by inversion of the *E* olefin: Koreeda, M.; Koizumi, N.; Teicher, B. A. *J. Chem. Soc., Chem. Commun.* **1976**, 1035) was very slow and provided a nearly 1:1 mixture of 20*S*,22*S* and 20*R*,22*R* product with 9-BBN. Hydroboration with borane–methyl sulfide was more selective (5.2:1, 20*S*,22*S*), but hydroboration of the 5(6) double bond became a serious problem.

The highly anti-Cram selectivity of these reactions prompted us to reexamine the reduction of the corresponding ketone, pregnenolone (eq 3). As expected,[9] typical nucleophilic reducing



(3)

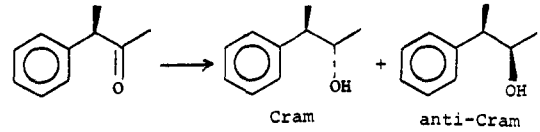
20S 20R

4 5 6

agents provide the 20*R* product (HPLC, Table I). Hindered trialkylborohydrides[10] provide nearly 99% epimeric purity. (However, it is interesting to note that potassium tri-*sec*-butylborohydride is considerably less selective than the lithium salt.[11])

Attention was then turned to electrophilic-type reducing agents. Again, as expected, borane–methyl sulfide (BMS) gives the 20*R* alcohol. However, the more sterically demanding 9-BBN gives only a slight excess of the 20*R* alcohol. The selectivity completely reverses with the more hindered dicyclohexyl- and disiamylboranes (Table I).[12] This reversal was most surprising since it has been reported that dialkylboranes reduce substituted cyclohexanones in the same sense and with nearly the same stereoselectivity as trialkylborohydrides.[13]

In order to ascertain whether the reversal was a peculiarity of the steroid system, the reduction of 3-phenyl-2-butanone was investigated (eq. 4). Lithium tri-*sec*-butylborohydride gives the

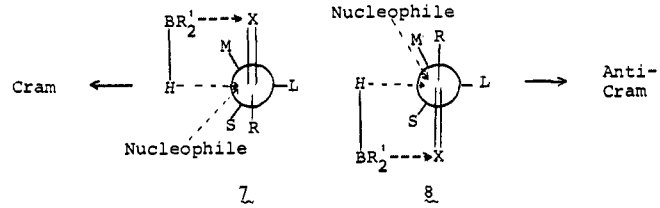


(4)

Cram anti-Cram

expected Cram product (22:1). However, dicyclohexylborane and disiamylborane give the anti-Cram product in selectivities of 2.8–4.1:1.[16]

The stereochemistry of nucleophilic additions to ketones has been postulated by Anh[28] to occur from a conformation that places the entering group in an antiperiplanar arrangement with the largest group at the adjacent chiral center. The trajectory of nucleophilic addition then brings the nucleophile over the smallest group as depicted in model 7. Recently, Houk has postulated



7 8

that hydroboration of olefins containing a chiral center adjacent to the point of attachment of boron may proceed from a conformation that rotates the olefin 180° from Anh's model.[14]

(9) Fieser, L. F.; Fieser, M. "Steroids"; Reinhold: New York, 1959; p 567.

(10) K- and L-Selectride and NB-Enantride are trademarks of Aldrich Chemical Co. NB-Enantride is a chiral borohydride. Midland, M. M.; Kazubski, A. *J. Org. Chem.* **1982**, *47*, 2495. Thus, one may expect a double asymmetric induction. However, NB-Enantride normally provides the *S* enantiomer.

(11) The decrease in selectivity with the potassium compound was somewhat surprising since the potassium reagent is slightly more selective in reductions of substituted cyclohexanones than the lithium reagent (Brown, C. A. *J. Am. Chem. Soc.* **1973**, *95*, 4100). A 19:1 *R*:*S* ratio has recently been reported for reduction of 20-oxopregnanes with K-Selectride (Göndös, G.; Orr, J. C. *J. Chem. Soc., Chem. Commun.* **1982**, 1239).

(12) From a practical point of view, the reductions with substituted organoboranes must be done with excess reducing agent (4 equiv) at room temperature or 0 °C. Forcing conditions lead to diminished stereoselectivities due to disproportionation of the organoborane and eventual reduction by a monoalkylborane or borane itself.

(13) Brown, H. C.; Varma, V. *J. Org. Chem.* **1974**, *39*, 1631.

(14) Paddon-Row, M. N.; Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1982**, *104*, 7162. We thank Professor Houk for a preprint of this article.

Houk's calculations support the experimental results obtained by Kishi, Evans, and Still.[15] Modification of Houk's model to rationalize our results leads to model **8** (X = CH_2, CHR, O). This model provides minimal steric interactions by placing the alkyl groups (R′) on boron in proximity with the small group of the chiral center. However, there is an increased steric repulsion of the R group with the M group in this model. Thus, in reduction of the ketone with a small reducing agent, BH_3, the model leading to the Cram product is apparently favored. In the case of an olefin (X = CH_2, CHR), one can postulate that model **7** is further destabilized by the interaction of the vinyl groups with the medium group. Thus, hydroboration of the olefin is more selective than reduction of the ketone with similar reagents.

In summary, the reduction of acyclic chiral ketones, unlike the cyclic examples, proceeds via different stereochemical pathways when performed by nucleophilic or electrophilic reducing agents. The anti-Cram selectivity observed in the hydroboration of the corresponding olefin is thus an example of this dichotomy. Although the models may not represent the actual transition state, they may be used in a predictive fashion. Finally, it is comforting to note that the experimental facts back up the theoretical predictions.

Acknowledgment. We thank the National Institutes of Health (Grants GM-24517 and GM-30081) for financial support of this work.

Registry No. 1, 38388-16-8; **2**, 55509-37-0; **3**, 85650-30-2; **4**, 1778-02-5; **5**, 53603-96-6; **6**, 14553-79-8; 3β,20*Z*-cholesta-5,20(22)-diene-3-ol acetate, 60132-90-3; 3β,20*E*-cholesta-5,20(22)-diene-3-ol acetate, 54548-85-5; thexylborane, 3688-24-2; disiamylborane, 6838-83-1; dicyclohexylborane, 1568-65-6; bis(*trans*-2-methylcyclohexyl)borane, 34611-76-2; 3-phenyl-2-butanone, 769-59-5; BMS, 13292-87-0; 9-BBN, 280-64-8; $NaBH_4$, 16940-66-2; $LiAlH_4$, 16853-85-3; $LiEt_3BH$, 22560-16-3; K-*s*-Bu_3BH, 67940-40-3; Li-*s*-Bu_3BH, 63717-73-7; NB-enantride, 81971-15-5.

(15) Kishi, Y. *Aldrichimica Acta* **1980**, *13*, 23. Schmid, G.; Fukuyama, T.; Akasaka, K.; Kishi, Y. *J. Am. Chem. Soc.* **1979**, *101*, 259. Evans, D. A.; Bartroli, J.; Godel, T. *Tetrahedron Lett.* **1982**, *23*, 4577. Still, W. C.; Barrish, J. C. *J. Am. Chem. Soc.* **1983**, *105*, 2487. The effect of oxygen substituents in these reactions remains to be explored.

(16) **Note Added in Proof**: Hydroboration of 2-methyl-3-phenyl-1-butene with bis(*trans*-2-methylcyclohexyl)borane provides the anti-Cram product as predicted by **8** (R = CH_3; X = CH_2; S = H; M = CH_3; L = C_6H_5) in a 10:1 ratio.

Electrophile-Induced Reduction of Coordinated Nitrogen Monoxide. Sequential Conversion of a μ_3-NO Group to μ_3-NOH and μ_3-NH Ligands by Protonic Acids[1]

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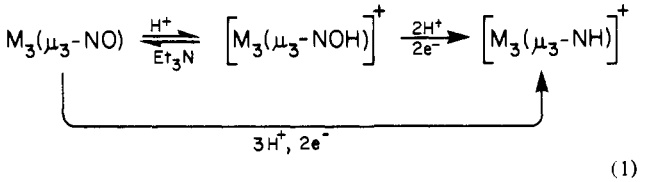
The principal impetus for the investigation of the reactivity of coordinated nitrogen monoxide derives from the widespread occurrence of nitrogen oxides as atmospheric pollutants.[2] Initial studies in this regard were focused primarily on the behavior of nucleophiles or electrophiles toward linear or bent M–NO linkages, respectively.[3] More recent research has begun to examine the analogous reactivity patterns of transition-metal complexes containing doubly bridging NO groups.[4,5] However, maximum reduction of the N–O bond order (and hence optimum activation of the bound NO) should occur in $M_3(\mu_3\text{-NO})$ systems. Accordingly, we have investigated the reactions of one such system with strong protonic acids and now report the unprecedented, sequential transformations shown in eq 1 (where M = (η^5-C_5H_4Me)Mn(NO)) which involve an overall formal reduction of the μ_3-NO ligand.



(1)

Addition of 1 equiv of acid [HBF_4·OMe_2 or HPF_6(aq)] to a CH_2Cl_2 solution of (η^5-$C_5H_4Me)_3Mn_3(NO)_4$ (**1**)[6] results in the rapid formation of [(η^5-$C_5H_4Me)_3Mn_3(NO)_3(NOH)$]Y (Y = BF_4, **2a**; Y = PF_6, **2b**).[7] (The reverse transformation, **2** → **1**, may

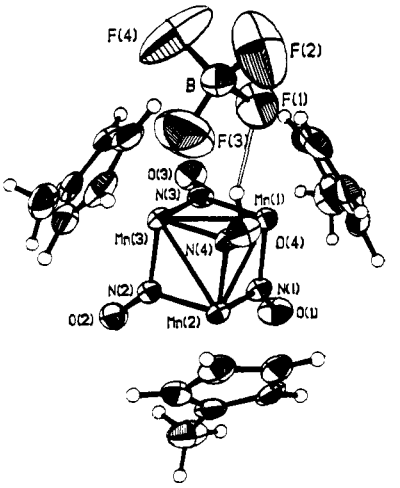


Figure 1. Molecular structure of **2a**. The hydrogen atoms have been assigned arbitrarily lower temperature factors for clarity. Selected bond lengths (Å) and angles (deg) are Mn–Mn (av) = 2.5083 (9), Mn–μ_2-N (av) = 1.856 (4), μ_2-N–O (av) = 1.207 (5), Mn–N(4) (av) = 1.873 (3), N(4)–O(4) = 1.393 (4), O(4)–H(NO) = 0.85 (6), H(NO)–F(1) = 1.91 (6), F(1)–B = 1.395 (6), B–F (av) = 1.321 (8), Mn–N(4)–Mn (av) = 84.1 (2), Mn–N(4)–O(4) (av) = 129.3 (2), N(4)–O(4)–H(NO) = 107 (4), O(4)–H(NO)–F(1) = 156 (6), H(NO)–F(1)–B = 112 (2).

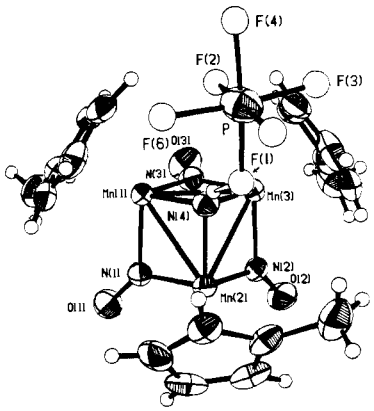


Figure 2. Molecular structure of **3b**. The hydrogen and fluorine atoms have been assigned arbitrarily lower temperature factors for clarity. Selected bond lengths (Å) and angles (deg) are Mn–Mn (av) = 2.5027 (7), Mn–μ_2-N (av) = 1.860 (3), μ_2-N–O (av) = 1.205 (4), Mn–N(4) (av) = 1.872 (3), N(4)–H = 0.81 (3), H–F(1) = 2.24 (4), P–F (av) = 1.528 (4), Mn–N(4)–Mn (av) = 83.95 (12), Mn–N(4)–H (av) = 129 (3), N(4)–H–F(1) = 165 (3).

(1) Organometallic Nitrosyl Chemistry. 18. For part 17 see: Legzdins, P.; Nurse, C. R. *Inorg. Chem.* **1982**, *21*, 3110.

(2) Eisenberg, R.; Hendriksen, D. E. *Adv. Catal.* **1979**, *28*, 79 and references therein.

(3) McCleverty, J. A. *Chem. Rev.* **1979**, *79*, 53.

(4) (a) Hames, B. W.; Legzdins, P.; Oxley, J. C. *Inorg. Chem.* **1980**, *19*, 1565. (b) Ball, R. G.; Hames, B. W.; Legzdins, P.; Trotter, J. *Ibid.* **1980**, *19*, 3626.

(5) Stevens, R. E.; Gladfelter, W. L. *J. Am. Chem. Soc.* **1982**, *104*, 6454.

(6) Kolthammer, B. W. S.; Legzdins, P. *J. Chem. Soc., Dalton Trans.* **1978**, 31.

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