Transformations of Chiral Iron Complexes Used in Organic Synthesis. Reactions of η^5-CpFe(PPh_3)(CO)$COCH_3$ and Related Species Leading to a Mild, Stereospecific Synthesis of β-Lactams

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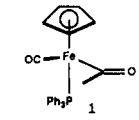
Abstract: Deprotonation of the stable organometallic acyl η^5-CpFe(PPh_3)(CO)$COCH_3$ with lithium diisopropylamide in THF at −42 °C generates a deep red-brown solution of a stable iron acyl enolate. Solutions of this enolate have been shown to undergo high-yield reactions with alkylating agents, carbonyl compounds, imines, and nitrones. In the presence of appropriate metal salt additives (R_2AlCl and $SnCl_2$), most of the reactions can be made to occur with very high diastereocontrol. The aldol products formed from condensation of the enolate with aldehydes can be dehydrated via the intermediacy of the β-acetoxy iron acyls to provide an excellent route to α,β-unsaturated iron acyls. The α,β-unsaturated iron acyls, in turn, react with exceptional stereocontrol with organolithium nucleophiles (RLi and R = alkyl and aryl; RNHLi and R = alkyl, allyl, and benzyl) via a 1,4-addition pathway. The enolate intermediates formed by 1,4-addition of the nucleophiles can be protonated or alkylated in high yield, and the alkylated products are formed in most cases with very high diastereoselectivity. The β-amino iron acyl products formed by the reaction of imines with the iron acyl enolate, by Ti(III) reduction of the hydroxyamino intermediates formed when the enolate of the parent iron acyl is condensed with nitrones, or by conjugate addition of RNHLi to the α,β-unsaturated iron acyls all give β-lactams in good to very good yields on oxidation with Br_2 (or I_2 in some cases) in nonprotic solvents at low temperature. A new model has been proposed to rationalize the diverse stereochemical results obtained for the various reactions described above.

Since the demonstration by Brunner[3] that the pseudooctahedral[4] complex η^5-CpFe(PPh_3)(CO)$COCH_3$, **1**, and related organometallic molecules could be prepared in optically active form and were configurationally stable under ambient conditions, much work has focused on using optically active organoiron substrates to gain information about organometallic reaction mechanisms.[6] We became interested in studying the chemistry of acyl **1** for two reasons. Previous to 1982 when we began this project, no report had appeared in the literature that described the attempted generation of the *enolate* of an organometallic acyl species.[7] Given the seminal role of organic carbonyl compound enolates in organic synthesis and the importance of transition-metal acyls in many metal-catalyzed processes, a study of the formation of enolates of metal acyl compounds appeared fundamentally interesting. Furthermore, in the event of successful metal acyl enolate generation from the chiral iron complex **1**, the possibility existed for using the iron chirality to induce asymmetry (relative or absolute) in the reaction of the iron acyl enolate with prochiral substrates. We were aware of a reported cleavage of an η^5-CpFe(L)(CO)COR



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species to a carboxylic acid derivative,[8] and we felt that the iron complexes could be used as "chiral enolate equivalents".[9] Why study a chiral transition-metal acyl enolate when a large number of excellent traditional organic systems are known? The use of transition-metal-based chirality for asymmetric induction is interesting for two reasons. First, metal-based chirality can occur in a number of geometries inaccessible to organic compounds. Numerous examples of five- and six-coordinate chiral geometries are known.[10] Second, steric and electronic perturbations to the inducing chiral center should be achievable with great flexibility in the organometallic system simply by varying the ligands about the metal. Purely organic systems seem inherently less flexible.

This manuscript contains complete details of our studies of the generation of the enolate of **1** and its reaction with various electrophiles including prochiral aldehydes and imines. Conversion of **1** by an aldol reaction and then dehydration into chiral α,β-unsaturated iron acyls is also described, and the incredibly stereoselective and high-yield conjugate addition and conjugate addition–alkylation reactions of these enoate systems with nucleophiles (RLi and RNHLi) is described. Adaptation of the described chemistry to a mild, efficient, and stereoselective synthesis of β-lactams is discussed. Aspects of this chemistry have been previously communicated,[11-15] and very similar results have

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(4) Davies and Seeman[5] have argued that complexes of η^5-CpFe(PPh_3)(CO)R should be referred to as pseudooctahedral rather than pseudotetrahedral based upon bond angles observed in X-ray crystal structures of a number of compounds.

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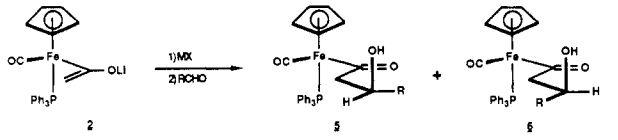
Table I. Influence of Counterion on the Aldol Stereoselectivity. Reaction of PhCHO with **2**

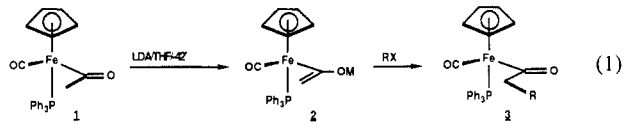


entry	additive	diastereomer ratio (**6**:**5**, R = Ph) and yield at −100 °C	−78 °C	−78 °C → room temp
1	Et_2AlCl	2.7:1.0 (78%)	3.5:1.0 (81%)	3.5:1.0 (76%)
2	i-Bu_2AlCl	6.2:1.0 (85%)	3.7:1.0 (70%)	3.2:1.0 (84%)
3	i-$BuAlCl_2$	1.3:1.0 (85%)		1.5:1.0 (65%)
4	$ClTi(O\text{-}i\text{-}Pr)_3$	1.3:1.0 (79%)	1.0:1.0 (75%)	1.0:1.0 (77%)
5	$MgBr_2$	1.0:1.3 (77%)	1.1:1.0 (69%)	1.0:1.1 (52%)
6	$SnCl_2$	too slow	1.0:13.3 (66%)	1.0:11.0 (71%)
7	$SnCl_2$, 2 equiv			1.0:12.0 (72%)
8	$SnBr_2$		1.0:11.6 (33%)	
9	SnI_2			no reaction
10	$Sn(OSO_2CF_3)_2$		1.0:1.9 (38%)	1.0:1.6 (80%)
11	Cp_2ZrCl_2	too slow	1.0:4.8 (39%)	1.0:2.9 (66%)

been independently reported by the Davies group at Oxford.[5,16-28] Related studies on acyls of η^5-CpFe(CO)$_2$ have been reported by other workers.[29,30]

Results

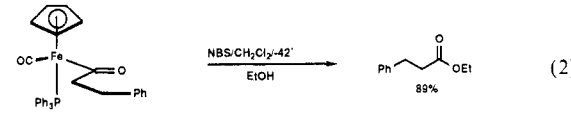
Treatment of an orange THF solution of η^5-CpFe(PPh$_3$)(CO)COCH$_3$, **1**, with lithium diisopropylamide at −42 °C produced a stable, deep red-brown solution of the lithium enolate **2**, M = Li. When kept at low temperature the enolate was indefinitely stable, but when warmed to 0 °C, noticeable decomposition occurred. Addition of alkylating agents to the solution of enolate **2** at −42 °C resulted in a color change back to orange and formation of carbon alkylated products **3** in high yield (eq 1).



(1)

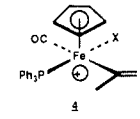
R	%
a, MeI	78
b, EtI	81
c, allyl-Br	78
d, $PhCH_2Br$	91

Efficient alkylation required the use of alkyl iodides, simple alkyl chlorides were unreactive, and alkyl bromides were sluggishly reactive. However, allyl bromide and benzyl bromide reacted well. The products were very stable orange solids that chromatographed easily on SiO_2 or Al_2O_3 and were soluble in relatively nonpolar solvents such as CH_2Cl_2, THF, or EtOAc. Typical infrared spectra for η^5-CpFe(PPh$_3$)(CO)COR show terminal CO absorptions near 1920 cm^{-1} and the acyl CO stretch near 1600 cm^{-1}. These iron acyl complexes are true carboxylic acid synthons; mild oxidation of the acyls in ethanol gave organic esters in high yield. However, choice of the oxidation conditions is critical to the success of this reaction. We have found that Br_2 in alcohol at 0 °C or above does not *always* cleanly produce the desired organic fragment. Successful use of Br_2 as an oxidant can often be achieved at low temperature (see below for successful use of Br_2 at −78 °C); however, *N*-bromosuccinimide (NBS) in EtOH/CH_2Cl_2 effected clean ester formation at −42 °C. When NBS was used in EtOH with CH_2Cl_2 cosolvent for solubility, iron acyl **3d** was cleaved at −42 °C to ethyl dihydrocinnamate in 89% yield (eq 2). The



(2)

mechanism of oxidative cleavage of these iron acyls is not known, but it is probable that the mechanism is similar to that established for the oxidation of iron alkyls[31] and proceeds through the acylium ion equivalent **4**. Decomposition of **4** to an acid halide that reacts with the alcoholic solvent or direct nucleophilic attack of the alcohol on **4** could lead to the observed esters.



Having established the conditions for generation and reaction of the enolate **2**, M = Li, with alkylating agents, we next investigated its reaction with prochiral aldehydes. This reaction would generate a new chiral center in the condensation product, and the influence of the iron chiral center on the reaction could be probed from the racemic iron acyl by studying the ratio of diastereomeric products with ^{1}H NMR. Aldehydes reacted very rapidly with enolate **2**, M = Li, at temperatures between −42 and −100 °C to give very good yields of the diastereomeric aldol products **5** and **6**; however, no effective influence of the iron chirality on the product relative stereochemistry was observed (eq 3). Acetone also reacted efficiently to produce the corresponding β-hydroxy iron acyl in excellent yield.

(3)

R, R′	ratio	%
CH_3, H	1:1	93
Ph, H	1:1	84
t-Bu, H	1:1	69
CH_3, CH_3		71

Counterion effects have been documented to have a dramatic influence on the stereochemistry of organic enolate reactions.[9,32-49]

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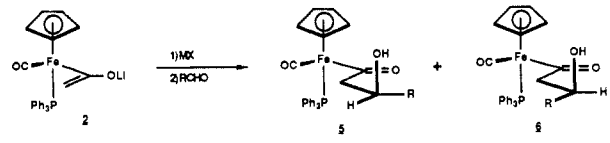
Table II. Aldol Stereoselectivity



	diastereomer ratio, 6:5, isolated yield					
counterion	MeCHO	EtCHO	*i*-PrCHO	PhCHO	PhCH=CHCHO	PrCH=CHCHO
i-Bu_2AlCl	4.4:1.0, 57%	5.2:1.0, 73%	8.2:1.0, 76%	3.5:1.0, 81%	1.7:1.0, 68%	2.5:1.0, 82%
$SnCl_2$	1.0:5.4, 60%	1.0:11.6, 66%	1.0:11.0, 74%	1.0:13.3, 66%	1.0:5.5, 44%	1.0:4.4, 56%

Following this lead, we added a number of metal salts to a THF solution of the lithium enolate, **2**, performed the aldol reaction with PhCHO, and assumed that any change in the stereoselectivity of the reaction leading to products **5** and **6** (R, R′ = Ph, H) could be attributed to exchange (or interaction) of the lithium enolate with the additive. This tactic proved quite successful and led to the results listed in Table I. Unless otherwise noted, 1.1–1.2 equiv of additive were used in each reaction, reported yields are based on material isolated after chromatography, all mass balances were >80%, and ratios of diastereomers were determined by integration of the well-resolved cyclopentadienyl or methylene proton resonances of the high-field ^1H NMR spectra (use of C_6D_6 as an NMR solvent was often required to cleanly separate the absorbances). Because of the inherent modest precision of the NMR integral, small changes in the diastereomer ratios were not considered significant. Correlation of spectral assignments with relative stereochemistry is described below. The wide variety of results listed in the table bring to light a number of points regarding the reaction (a detailed analysis will be presented in the Discussion section). Most noteworthy is the observation that either of the diastereomeric products **5** or **6** could be made to predominate by the proper choice of counterion. It appears that the more electropositive counterions (Al, Ti, and Mg) tend to favor formation of diastereomer **6**, while the less electropositive metals (Sn and Zr) favor formation of diastereomer **5**. For formation of diastereomer **6**, the best yield and stereoselectivity was achieved with *i*-Bu_2AlCl, while diastereomer **5** was made to predominate with excellent stereocontrol when $SnCl_2$ was the additive. Reaction conditions were chosen to assess whether the observed stereoselectivities were induced by kinetic or thermodynamic control, and no significant evidence of equilibration was detected when the data for the three reaction conditions designated in Table I were compared. This was further probed for the *i*-Bu_2AlCl reactions of PhCHO by quenching the −78 °C reaction mixture after 30 s, 1 h, and 6 h with no change in the diastereomer ratios (3.6–3.7:1.0).

Next we took our two best systems, *i*-Bu_2AlCl and $SnCl_2$, and surveyed a number of different aldehydes in the aldol reaction using these counterion additives. These results are shown in Table II and establish the generality of the stereoselective aldol reaction first probed with PhCHO. All reactions were done at −78 °C and quenched at that temperature. In general the $SnCl_2$ reactions gave much better stereocontrol than the *i*-Bu_2AlCl runs, and in both systems the α,β-unsaturated aldehydes were less diastereoselective than the aliphatic or aromatic aldehydes. The steric bulk of the aldehyde R group seems to play some role in the stereocontrol as seen by comparing the MeCHO, EtCHO, and *i*-PrCHO results.

Table III. Attempts to Reproduce Results Described in Reference 17

entry	base	conditions	isolated yield, %	ratio (6:5)
1	1.1 equiv of LDA, −78 °C	1.1 equiv of Et_2AlCl, −42 °C, 45 min	40	1.3:1.0
2	1.1 equiv of *n*-BuLi, −78 °C	1.1 equiv of Et_2AlCl, −42 °C, 45 min	67	1.1:1.0
3	2.3 equiv of *n*-BuLi, −78 °C	1.1 equiv of Et_2AlCl, −42 °C, 45 min	79	1.0:1.5
4	2.3 equiv of *n*-BuLi, −78 °C	2.3 equiv of Et_2AlCl, −42 °C, 45 min	79	1.3:1.0
5	2.3 equiv of *n*-BuLi, added to **1**	2.3 equiv of Et_2AlCl, −42 °C, 45 min	76	1.1:1.0
6	1.5 equiv of *n*-BuLi	3.0 equiv of Et_2AlCl, −42 °C, 45 min	74	2.4:1.0
7	1.1 equiv of *n*-BuLi	4.0 equiv of Et_2AlCl, −42 °C, 45 min	47	1.5:1.0
8	1.2 equiv of *n*-BuLi	1.3 equiv of Et_3Al, −42 °C, 45 min	82	1.0:4.6
9	1.3 equiv of *n*-BuLi, 20% HMPA	1.3 equiv of Et_3Al, −42 °C, 45 min	58	7.3:1.0
10	2.0 equiv of *n*-BuLi, −78 °C	5.0 equiv of Et_2AlCl, −42 °C, 45 min	85	36:1.0

After we had accumulated many of these results and our aldol communication was in press,[13] a short article and then a full paper appeared from the Davies group claiming that addition of Et_2AlCl to the lithium enolate of iron acyl **1** caused the aldol reaction to proceed with very high diastereocontrol of >100:1 in favor of diastereomer **6**.[17] Since the best stereoselectivity we could achieve with either Et_2AlCl or *i*-Bu_2AlCl was on the order of 8:1, we performed a more thorough study of the variables in the aluminum system. The results of a number of aldol reactions using *i*-PrCHO are listed in Table III. All reactions were run 0.05 M in enolate with the deprotonation achieved at −78 °C, the counterion exchange performed at −42 °C, and the aldehyde addition and reaction quench conducted at −95 °C. Lithium diisopropylamide and *n*-BuLi gave similar stereochemical results under the same reaction conditions with the lower yield for the LDA reaction attributed to the slow deprotonation of acyl **1** by LDA at −78 °C (entries 1 and 2). The order of the addition of the base had little effect on the **5**:**6** ratio. Addition of HMPA did have a beneficial influence on the stereoselectivity (entry 9), and substituting Et_3Al for Et_2AlCl caused the diastereomer ratio to favor diastereomer **5** rather than **6** as seen for all the other aluminum results. Most significantly, these experiments did demonstrate the significant influence of both additive and base stoichiometry on the stereoselectivity of the aldol reaction. *Only* when 2 equiv of base (*n*-BuLi) and 5 equiv of Et_2AlCl were added to 1 equiv of iron acyl **1** could the results of Davies be reproduced. In the recent full paper describing his aldol results,[17] Davies mentioned the necessity of using excess aluminum reagent to achieve good stereocontrol, but he did not point out that his routine use of excess base (2 equiv) was also critical to successful application of this chemistry. Our efforts to corroborate the published results in

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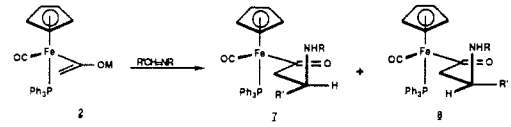
Table IV. Stereoselective Imine Condensations

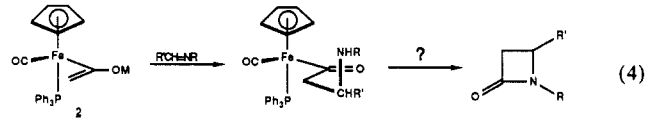


entry	imine	counterion	isolated yields, %	diast. ratio (7:8)
1	(*E*)-PhCH=NPh	Li	85 (−78 °C)	5.7:1.0
2	(*E*)-PhCH=NPr	Et_2AlCl	80	20:1.0
3	(*E*)-*i*-PrCH=NPr	Et_2AlCl	68	20:1.0
4	(*E*)-PhCH=NC_6H_{11}	Et_2AlCl	54	20:1.0
5	(*E*)-*i*-PrCH=NC_6H_{11}	Et_2AlCl	57	20:1.0
6	(*E*)-PhCH=NCH_2Ph	Et_2AlCl	75	25:1.0
7	(*E*,*E*)-PhCH=CHCH=NPr	Et_2AlCl	44	2.5:1.0
8	(*E*,*E*)-PhCH=CMeCH=NPr	Et_2AlCl	53	11.5:1.0
9	(*E*,*E*)-PhCH=CHCH=N-(*p*-$(CH_3OC_6H_4)$	Et_2AlCl	68	1.3:1.0
10	(*E*,*E*)-EtCH=CMeCH=NPr	Et_2AlCl	37	20:1.0
11	5,5-dimethyl-1-pyrroline	*i*-Bu_2AlCl	80	1.3:1.0

question made one point distinctly clear: a "simple" aluminum enolate was probably not responsible for the excellent stereoselectivity observed in the aluminum chemistry. Mechanistic questions aside, when the stoichiometry described above is rigorously followed, the aluminum enolate conditions do provide excellent control over the stereochemistry of the aldol reaction.

Assignment of structure to the aldol diastereoisomers was achieved in the following manner. The relative configuration of the chiral centers in the major diastereomer of the $SnCl_2$-modified reaction of enolate **2** with PhCHO, **5** (R = Ph), was rigorously determined by X-ray diffraction analysis (refer to supplementary material) and established the *SS*:*RR* relative stereochemistry of the product (PPh_3 and Ph syn as drawn in **5**). This necessarily dictated the *SR*:*RS* structure **6** (PPh_3 and Ph anti) to the major isomer of the *i*-Bu_2AlCl-based reaction of PhCHO and enolate **2**. In order to confidently assign the same relative stereochemistry to the tin-based and aluminum-based predominant diastereomers resulting from the aldol reaction of the other aldehydes, a careful analysis of the high-field ^1H NMR spectra was undertaken for each family of reactions. This analysis showed a general pattern for the appearance of the methylene hydrogens adjacent to the acyl carbon of diastereomers **5** and **6** that suggested all major products of the tin reactions had the same relative stereochemistry as verified for **5**, R = Ph, and all major products of the aluminum reactions had the same relative stereochemistry as **6**, R = Ph. In all cases investigated, the ^1H NMR spectra taken in C_6D_6 showed the methylene proton absorptions of the aluminum major isomer resonating *between* the chemical shifts of the methylene hydrogens of the tin major isomer. As a general rule, for either diastereomer the higher field methylene hydrogen had a larger vicinal coupling constant to the adjacent methine than did the lower field methylene hydrogen. Occasionally, the coupling patterns for the Al major isomer were partially obscurred by overlapping OH resonances.

On considering other possible uses of the chiral iron enolate, we realized that a successful condensation of imines with **2** would provide us with β-amino iron acyls, a functional group relationship with potential application to the synthesis of β-lactams (eq 4).



(4)

Although there appears to be more than one pathway for formation of β-lactams from organoiron species,[50] Rosenblum had previously shown that oxidation of a chelated β-amino iron alkyl gave a β-lactam.[51] If imines would condense with the iron acyl enolate, the β-amino iron acyl products could give β-lactams on oxidation in a nonnucleophilic solvent. A number of other β-lactam syntheses using transition-metal intermediates have been described.[52]

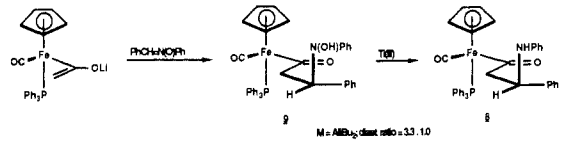
Initial attempts to induce reactions of imines were performed with **2**, M = Li, and although benzylideneaniline (PhCH=NPh) reacted very well,[20] other imines did not. Simply adding 1.2–1.5 equiv of Et_2AlCl to the lithium enolate, **2**, at −42 °C produced a species that condensed with reasonable efficiency, although slowly, with a wide variety of imines. Table IV lists the various results we have obtained on the imine condensation chemistry along with the stereoselectivity of the reaction. All reactions gave very high mass balances with the remainder of the reaction product recovered being acyl **1** in all cases. Most apparent in the table is the exceptional control over diastereoselectivity in the reaction of *E* imines even at −42 °C. Most imines condensed far more sluggishly with **2** than the aldehydes, and this poor reactivity is probably responsible for the moderate yields that are seen in some entries. Thiazolines and oxazolines were found to be unreactive to all iron acyl enolates tried, probably because of reduced electrophilicity of the carbon–nitrogen double bond. As in the aldehyde condensation, imines derived from simple α,β-unsaturated aldehydes reacted with significantly lower stereoselectivity than other substrates, and the one *Z* imine tested, 5,5-dimethyl-1-pyrroline, also showed low stereocontrol. Particularly interesting were the results with imines prepared from α-methyl-substituted α,β-unsaturated aldehydes which gave much improved diastereomer ratios over the reactions with the cinnamaldehyde-derived imines. Rationalizations of these different results will be presented below.

The assignment of relative stereochemistry **7** to the imine condensation diastereomers was achieved by a combination of X-ray crystallography and high-field ^1H NMR. A single crystal of the major diastereomer formed from reaction of PhCH=NPh was subjected to an X-ray crystal structure determination and confirmed the relative stereochemistry, *SR*:*RS*, of the major product **7**, R = Ph (refer to supplementary material). Once again consistencies in the ^1H NMR spectra of the major and minor diastereomers were used to assign structure **7** to all major isomers of the imine condensation reactions. In all cases investigated, when comparing the appearance of the methylene protons adjacent to the acyl carbon of the major diastereomer, the higher field hydrogen always showed a smaller vicinal coupling constant to the hydrogen adjacent to the nitrogen than did the lower field methylene hydrogen. When the minor diastereomer formed in the imine condensations could be observed, it had reversed magnitudes of vicinal coupling constants to the higher and lower field methylene hydrogens. This conformity of the NMR spectra

(50) Javaheri, S.; Giering, W. P. *Organometallics* **1984**, *3*, 1927.
(51) Wong, P. K.; Madhavarao, M.; Marten, D. F.; Rosenblum, M. *J. Am. Chem. Soc.* **1977**, *99*, 2823.
(52) Berryhill, S. R.; Rosenblum, M. *J. Org. Chem.* **1980**, *45*, 1984. Berryhill, S. R.; Price, T.; Rosenblum, M. *J. Org. Chem.* **1983**, *48*, 158. Alper, H.; Urso, F.; Smith, D. J. H. *J. Am. Chem. Soc.* **1983**, *105*, 6737. Hegedus, L. S.; McGuire, M. A.; Schultze, L. M.; Yijun, C.; Anderson, O. *J. Am. Chem. Soc.* **1984**, *106*, 2680. Hodgson, S. T.; Hollinshead, D. M.; Ley, S. V. *J. Chem. Soc., Chem. Commun.* **1984**, 494. Mori, M.; Chiba, K.; Okita, M.; Ban, Y. *J. Chem. Soc., Chem. Commun.* **1979**, 698.

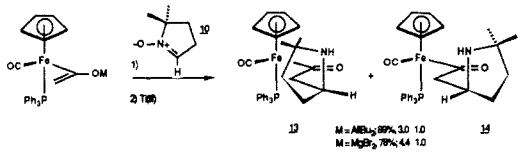
was used to justify assignment of relative stereochemistry to the imine condensation products.

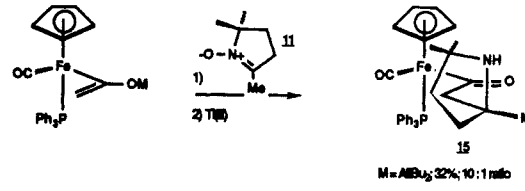
In an effort to overcome the poor electrophilicty of imines, we next investigated the use of nitrones as electrophilic partners for reaction with the iron acyl enolates. PhCH=N(O)Ph reacted rapidly with the aluminum-based enolate at −78 °C to give a good yield (68%) of a product that was not stable to chromatography but showed IR and ^{1}H NMR spectra consistent with the anticipated β-hydroxyamino iron acyl **9**. It was discovered that treatment of this crude product with aqueous $TiCl_3$ in THF at room temperature caused a selective reduction of the N–O bond and delivered in 99% yield a 3.3:1.0 ratio of β-amino iron acyl diastereomers, the predominant isomer being identical with **8**, R = R^1 = Ph, which was the minor product formed when PhCH=NPh was condensed with the aluminum enolate (relative stereochemistry *SS*:*RR*; eq 5). This mild and selective reduction

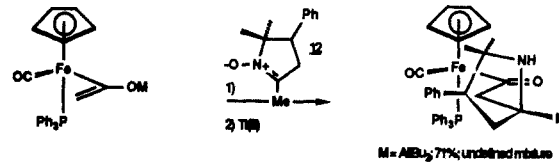


(5)

of the primary product of nucleophilic addition to the nitrone is worth emphasizing, because it demonstrates that the η^5-CpFe(CO)(PPh_3) unit will survive organic transformations on other portions of a molecule. A brief survey of cyclic nitrones **10–12** was undertaken and established the generality of this alternative two-step route to β-amino iron acyl complexes. Examples are given in eq 6–8. When the aluminum or magnesium variations of the


(6)


(7)

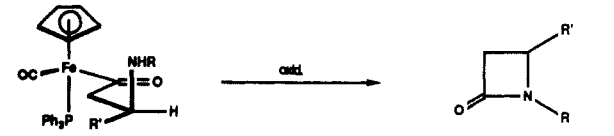

(8)

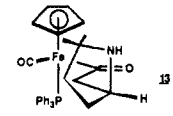
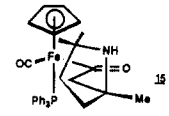
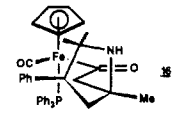
iron acyl enolate were used, reactions were rapid and yields were high with aldonitrones. Other counterions reacted much more slowly and gave inferior yields. Stereochemical assignments of the reactions with the cyclic nitrones were based upon the results seen with the acyclic nitrone, PhCH=N(O)Ph. Since a variety of spectroscopic studies have established that aldonitrones exist in the *E* configuration,[53] we could work from the PhCH=N(O)Ph results, which were rigorously tied to the β-amino iron acyl observations described previously, and then assign relative stereochemistry to the case of the cyclic substrates by presuming the same transition-state model for cyclic and acyclic nitrones (see below).

With a wide variety of β-amino iron acyl products available from both the imine and nitrone reactions, we surveyed these substrates as potential β-lactam precursors as alluded to above. Table V lists our results. Our first attempts at oxidative cleavage of the amino acyl compounds were with NBS, an oxidant that had been successful in the preparation of esters from the iron acyls. However, treatment of amino acyl **7** (R = R′ = Ph) with NBS

(53) Hamer, J.; Maculuso, A. *Chem. Rev.* **1964**, *64*, 473.

Table V. Synthesis of β-Lactams from β-Amino Iron Acyls



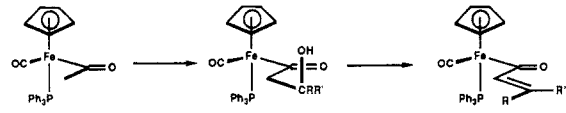
entry	R′	R	reaction conditions	β-lactam yield, %
1	Ph	Ph	NBS/CH_2Cl_2/−42 °C	10[a]
2	Ph	Ph	I_2/CH_2Cl_2/$PhNMe_2$/ room temp	57[b]
3	Ph	Ph	I_2/CH_2Cl_2/$PhNMe_2$/ −42 °C	80
4	Ph	*n*-Pr	I_2/CH_2Cl_2/$PhNMe_2$/ room temp	70
5	Ph	*n*-Pr	Br_2/CS_2/−42 °C	82
6	Ph	CH_2Ph	Br_2/CS_2/−78 °C	79
7	Ph	C_6H_{11}	Br_2/CS_2/−78 °C	66
8	*i*-Pr	*n*-Pr	Br_2/CS_2/−78 °C	56
9	(*Z*)-C(Me)=CHPh	*n*-Pr	Br_2/CS_2/−42 °C	62
10			Br_2/CH_2Cl_2/−78 °C	31
11			Br_2/CS_2/−45 °C	56
12			$I_2/CH_2Cl_2/Et_3N$	62

[a] Product contained a monobrominated aromatic ring. [b] *N*-Phenyl-1-phenyl-2-iodoethane was also formed in this reaction in 40% yield.

in CH_2Cl_2 at −42 °C led to a low yield of a β-lactam that had incorporated a Br atom in one of the aniline aromatic rings (entry 1). Excess iodine in methylene chloride at room temperature in the presence of *N*,*N*-dimethylaniline produced the desired β-lactam in 57% yield; however, 1-(phenylamino)-1-phenyl-2-iodoethane, a decarbonylation product, was also produced in 40% yield under these conditions (entry 2). When the reaction temperature was lowered to −42 °C, the reaction proceeded more cleanly and the β-lactam was formed in 80% yield (entry 3). However, the propensity toward formation of the decarbonylation product was dependent on the structure of the β-amino iron acyl, since oxidation of **7** (R = Ph, R′ = *n*-Pr) with I_2 in CH_2Cl_2 at room temperature led to a 70% yield of the desired β-lactam (entry 4). We then discovered that 1 equiv of Br_2 in CS_2 at −78 °C (or in some cases at −42 °C) was far superior to I_2 as an oxidant for β-lactam formation in most cases studied. The presence of added base in these reactions did not seem to be required, and good to very good yields of β-lactams were formed from all of the other acyclic systems tested (entries 5–9 of Table V). Noteworthy is the fact that aliphatic and aromatic groups were tolerated at both of the substituent positions. The β-amino iron acyls derived from nucleophilic addition to the cyclic nitrones gave good yields of their corresponding β-lactams (entries 10 and 11), with an exception noted with entry 10, where the low yield of β-lactam was attributed to sensitivity of the compound to chromatography. In general, oxidation of β-amino iron acyls at low temperature provided a very mild method for the synthesis of β-lactams. Additional examples with more highly substituted systems can be seen below.

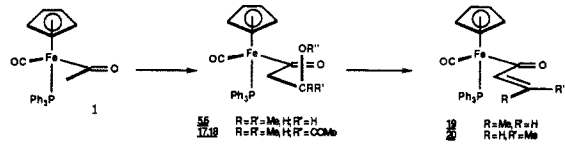
Having established the unique ability of η^5-CpFe(CO)(PPh_3)COMe to function as a chiral acetate synthon, we considered other possible uses of the η^5-CpFe(CO)(PPh_3) unit for control of stereochemistry in organic transformations. A study of α,β-unsaturated iron acyls was chosen because it offered the possibility of investigating reactions of an extended enolate (α vs. γ reaction and stereoselectivity) and of probing stereocontrol in the 1,4-addition of nucleophiles to an α,β-unsaturated iron acyl.

Table VI. Preparation of α,β-Unsaturated Iron Acyls



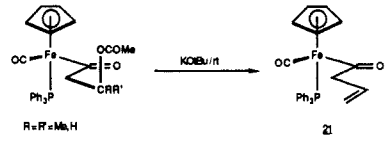
entry	R	R′	% aldol	% product	compd
1	Me	H	93	82	**19**
2	Ph	H	87	93	**22**
3	*i*-Pr	H	86	78	**23**
4	Me	Me	81	65	**24**
5	(*E*)-CH=CH-*n*-Bu	H	83	80	**25**

In order to maintain the eventual option of studying enantioselective reactions from an optically active substrate, we required a synthesis of α,β-unsaturated iron acyls from the parent compound, η^5-CpFe(CO)(PPh$_3$)COMe, **1**, for which a procedure for the synthesis of either enantiomer had been described.[3] A synthesis of α,β-unsaturated iron acyls was developed that involved standard organic transformations of **1** (eq 9). Aldol condensation of the



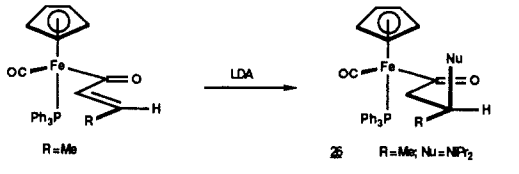
(9)

lithium enolate **2** with MeCHO gave, as described above, a 93% yield of a 1:1 mixture of diastereomers **5** and **6** (R = Me). Attempts to dehydrate this β-hydroxy iron acyl under standard acidic and basic conditions were not successful, so the hydroxy group was converted into a better leaving group. Treatment of the β-hydroxy iron acyl with MeLi at 0 °C followed by an acetic anhydride quench gave the corresponding β-acetoxy iron acyls **17** and **18** in 85% yield. Then, treatment with KO-*t*-Bu at 0 °C in THF readily eliminated the elements of acetic acid and produced the desired *E* α,β-unsaturated iron acyl **19** in 82% yield along with a trace (6%) of the *Z* isomer **20**. The success of this KO-*t*-Bu reaction is dependent on careful control of the reaction temperature, since allowing the reaction to run at room temperature caused substantial conversion of the α,β-unsaturated compound to the β,γ-unsaturated isomer **21** (51% isolated yield; eq 10). The sequence of reactions used for the synthesis of **19** was successfully applied to a number of other aldol products, and these results are listed in Table VI.



(10)

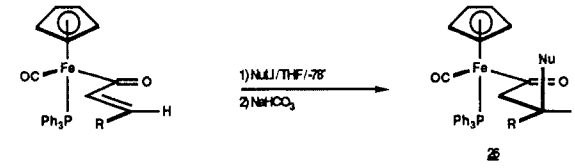
With a variety of α,β-unsaturated iron acyls in hand, we began an exploration of the reaction chemistry of these species. In an attempt to prepare an extended enolate, **19** was treated with LDA in THF at −78 °C. To our surprise, a fairly clean and highly stereoselective 1,4-addition reaction ensued to provide a 9:1 ratio of diastereomers in 47% yield with β-amino iron acyl **26** formed as the major isomer (eq 11). The 1,4-addition of LDA, a hindered



(11)

nucleophile, to enone **19** suggested to us that less-hindered systems might show an even greater tendency for conjugate addition to α,β-unsaturated iron acyls. As anticipated, lithium salts of primary amines and alkyl- and aryllithiums reacted at −78 °C with high efficienty in a 1,4-fashion with the crotonyl system **19** and the cinnamyl derivative **22** (Table VII). An unexpected benefit was the extremely high diastereoselection that occurred in these reactions. Reaction with the less basic aniline was significantly slower at −78 °C, and a reasonable reaction rate with the crotonyl system **19** was not achieved until the reaction temperature was raised to −42 °C. No reaction of PhNHLi with the cinnamyl derivative **22** was observed even at 0 °C. This last observation was not surprising, since we had previously discovered during our study of the imine condensation chemistry that reaction of the iron acyl enolate **2**, M = Li or AlEt$_2$, with PhCH=NPh at 0 °C gave the α,β-unsaturated iron acyl **22** (M = Li, 24%; M = AlEt$_2$, 69%). It would therefore appear that the addition of PhNHLi to **22** is readily reversible at 0 °C and that the equilibrium lies heavily on the enone side of the reaction. Attempts to add Grignard reagents, and the anions of primary amides, primary sulfonamides, and dimethylmalonate were all unsuccessful.

Table VII. Stereoselective Conjugate Addition of RLi and RNHLi to **19** and **22**

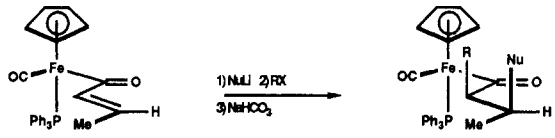


entry	R	Nu	diastereomer ratio	yield, %
1	Me	Bu	30:1	97
2	Me	Ph	30:1	98
3	Me	*n*-PrNH	31:1	97
4	Me	PhCH$_2$NH	30:1	99
5	Me	CH$_2$=CHCH$_2$NH	22:1	99
6	Me	MeOCH$_2$CH$_2$NH	30:1	69
7	Me	PhNH (−42 °C)	10:1	69
8	Ph	*n*-PrNH	22:1	66
9	Ph	CH$_2$=CHCH$_2$NH	31:1	79
10	Ph	MeOCH$_2$CH$_2$NH	18:1	63
11	Ph	PhNH (0 °C)		N.R.

Assignment of relative stereochemistry **26** to the products formed in these 1,4-addition reactions was based on two factors. First, in the addition of *n*-PrNHLi to **22** (entry 8, Table VII), the observed product was identical with the compound previously obtained from condensation of PhCH=N-*n*-Pr with the iron acyl enolate **2** (M = AlEt$_2$). Second, with the exclusion of the aniline adduct of entry 7, the high-field ^{1}H NMR spectra of all products prepared in Table VII and eq 11 showed the same consistent trends in chemical shift and coupling constants previously detailed for the major isomers formed in the addition of iron acyl enolate **2** (M = AlEt$_2$) to imines. In all cases investigated, when comparing the appearance of the methylene protons adjacent to the acyl carbon of the major diastereomer, the higher field hydrogen always showed a smaller vicinal coupling constant to the hydrogen adjacent to the nitrogen, than did the lower field methylene hydrogen. The inconsistent ^{1}H NMR spectrum for the product of the aniline reaction leaves assignment of it's relative stereochemistry in doubt, but we do not believe that the anomalous spectrum seen in this special instance detracts from the strength of the structure assignment of the other compounds. The very different reactivity of PhNHLi compared to the other nucleophiles used in the 1,4-addition reaction and the distinct possibility of product equilibration caused by reversibility of the 1,4-addition in the case of PhNHLi as a nucleophile (see above) make it a special case.

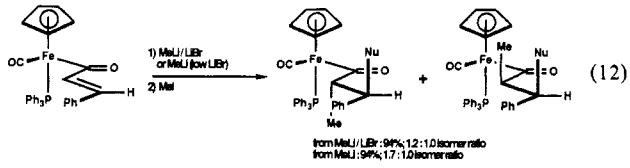
Since the conjugate addition of nucleophiles to **19** and **22** must proceed through the corresponding enolate in each case, we realized that the virtues of excellent stereocontrol bestowed upon the 1,4-additions could be extended to a conjugate addition and alkylation sequence with the η^5-CpFe(PPh$_3$)(CO) group dictating the stereochemistry at each of the two new stereocenters. In addition, this reaction sequence should open up a very facile stereospecific route to 2,3-disubstituted β-lactams. The results of this conjugate addition/alkylation study using the crotonyl system **19** are presented in Table VIII. Very high diastereoselectivity was observed for the addition of a series of nucleophiles followed by alkylation with a few simple alkylating agents. In all cases shown in the table, the diastereomer ratio refers to the

Table VIII. Stereoselective Conjugate Addition/Alkylation Reactions of **19**



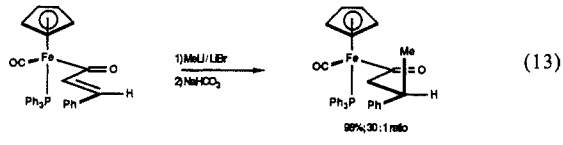
entry	Nu	RX	diastereomer ratio	isolated yield, %
1	Ph	MeI	30:1.0	93
2	$PhCH_2NH$	MeI	24:1.0	95
3	$PhCH_2NH$	EtI	20:1.0	99
4	$PhCH_2NH$	$PhCH_2Br$	15:1.0	99
5	$PhCH_2NH$	$CH_2{=}CHCH_2Br$	30:1.0	92
6	*n*-PrNH	MeI	10:1.0	53

ratio of ^1H NMR integrals observed for the major Cp resonance and any apparent minor Cp resonance. The stereochemistry of the major isomer was determined as described below, and no attempt was made to establish the stereochemistry of the minor isomer. Since the stereocontrol was so dramatic for all of the cases examined when the crotonyl system **19**, we were very surprised to observe a 1.2:1.0 ratio of diastereomers in the reaction of the cinnamyl iron complex **22** with MeLi/LiBr followed by alkylation with MeI (eq 12). This drastic decrease in stereoselectivity was



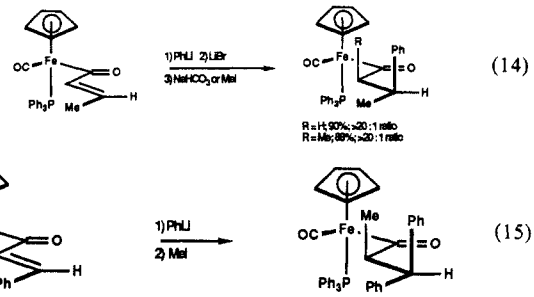
(12)

unexpected and undoubtedly of significance in any discussion of the factors that cause the η^5-CpFe(PPh$_3$)(CO) group to exert such phenomenal control over stereochemistry in most of the reactions investigated. We were therefore prompted to explore the origins of the reduced stereoselectivity in greater detail. Treatment of the cinnamyl complex **22** with MeLi/LiBr followed by an aqueous quench of the enolate gave the 1,4 adduct in eq 13 in 98% isolated



(13)

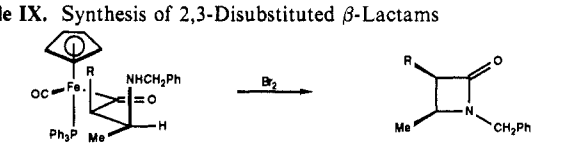
yield as a 30:1 ratio of diastereomers dictating that the loss of stereoselectivity originated in the alkylation step (eq 13). Since MeLi/LiBr was the only alkyllithium–lithium bromide complex used in our studies, we attempted conjugate addition with MeLi containing only traces of LiBr, but subsequent alkylation with MeI produced a 1.7:1.0 ratio of product diastereomers in 94% yield. In addition, adding LiBr to other reactions already known to give very high stereoselectivity had no detrimental effect on the reactions (eq 14). Most significantly, when PhLi was added to the cinnamyl iron complex and the intermediate enolate was trapped with MeI, very good stereoselectivity (11:1.0) was again observed in the products (eq 15), establishing that some property of MeLi was responsible for the loss of stereoselectivity in the previous reactions. This interesting effect is discussed below.



(14)

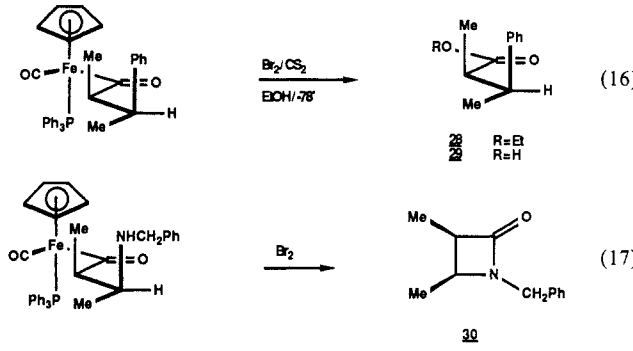
(15)

Table IX. Synthesis of 2,3-Disubstituted β-Lactams



entry	R	isolated yield, %
1	Me	78
2	Et	80
3	CH_2Ph	63
4	$CH_2CH{=}CH_2$	22

Since we knew the relative stereochemistry established in the 1,4-addition from our previous studies, we only had to determine the stereochemical relationship between the added nucleophile and the alkylated R group to pin down the stereochemistry of the major diastereomer formed in the conjugate addition/alkylation sequence. This was accomplished in two systems. The product formed in entry 1 of Table VIII was treated with Br_2 in CS_2/EtOH at −78 °C to give the known erythro ester **28** which was further characterized by hydrolysis to the known crystalline acid **29**,[54] confirming the *SRS*:*RSR* relative stereochemistry of the iron acyl product (eq 16). In a similar fashion, oxidative decomposition of the product formed in entry 2 of Table VIII gave the known cis disubstituted β-lactam **30**[51] in 78% yield, establishing the entry of both the nucleophile and the electrophile from the same prochiral face of the enone (eq 17).



(16)

(17)

The high-yield, stereospecific formation of β-lactam **30** suggested that the conjugate addition of amine anion nucleophiles to α,β-unsaturated iron acyls followed by alkylation would provide a simple, stereospecific route to 2,3-disubstituted β-lactams, and the four results shown in Table IX support this proposal. Although a low yield was obtained for the last entry in Table IX, the result is significant because it suggests that selective oxidative cleavage

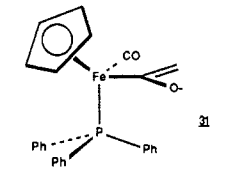
(54) Theine, A.; Traynham, J. G. *J. Org. Chem.* **1974**, *39*, 153.
(55) Bjorgo, J.; Boyd, D. R.; Watson, C. G.; Jennings, W. B.; Jerina, D. M. *J. Chem. Soc., Perkin Trans. 2* **1974**, 1081 and references therein.
(56) Davies, A. G.; Smith, P. J. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon: Elmsford, NY, 1982; Vol. 2, p 581.
(57) Eisch, J. J. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon: Elmsford, NY 1982; Vol. 1, p 555.
(58) Brown, H. C.; Rao, C. G.; Kulkarni, S. V. *Synthesis* **1979**, 704.
(59) Cordes, E. H.; Jencks, W. P. *J. Am. Chem. Soc.* **1963**, *85*, 2843.
(60) Tiollais, R. *Bull. Soc. Chim. Fr.* **1947**, 708. Layer, R. W. *Chem. Rev.* **1963**, 489.
(61) Wenker, H. *J. Am. Chem. Soc.* **1935**, *57*, 1079.
(62) Wheeler, O. H.; Gore, P. H. *J. Am. Chem. Soc.* **1956**, *78*, 3363. Utzinger, G. E.; Regenass, F. A. *Helv. Chim. Acta* **1954**, *37*, 1892. Dicken, C. M.; DeShong, P. *J. Org. Chem.* **1982**, *47*, 2047.
(63) Bapat, J. B.; Black, D. St. C. *Aust. J. Chem.* **1968**, *21*, 2483. Bonnett, R.; Clark, V. M.; Giddey, A.; Todd, A. *J. Chem. Soc.* **1959**, 2087. Bonnett, R.; Brown, R. F. C.; Clark, V. M.; Sutherland, I. O.; Todd, A. *J. Chem. Soc.* **1959**, 2094. Brown, R. F. C.; Clark, V. M.; Todd, A. *J. Chem. Soc.* **1959**, 2105.
(64) We thank Prof. Stephen Davies for pointing this fact out to us.
(65) This is functionally equivalent to the transition state previously proposed by Davies to account for conjugate additions to the unsaturated iron systems: ref 26 and 66f.

of the iron acyl will be feasible even in the presence of halogen-sensitive functional groups.

Discussion

Davies, in collaboration with Seeman, has developed a detailed model to explain the factors responsible for the high stereoselectivity observed in the alkylation, aldol, and conjugate addition/alkylation reactions of the CpFe(PPh$_3$)(CO) system.[5,66c-e] It is not our intention in this manuscript to attempt to provide the reader with another model to compete with that presented by Davies and Seeman. However, in the course of our studies of the imine condensations we came across a number of results that were not readily explained by their model, and we were forced to consider a modified rationalization to account for the imine chemistry. The reader is referred to the papers by Davies and Seeman on stereocontrol in the CpFe(PPh$_3$)(CO) system for contrast and comparison to the model we develop below.[5,66c-e]

The Davies–Seeman model states that all stereoselective reactions of the iron acyl enolate are explained in terms of an anti enolate (enolate O and CO anti), **31**, reacting from the face away from the PPh$_3$. An underlying presumption of the model is that



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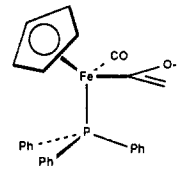

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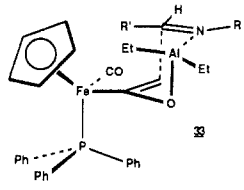

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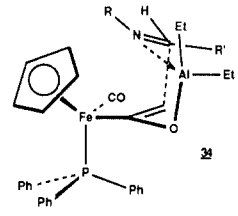
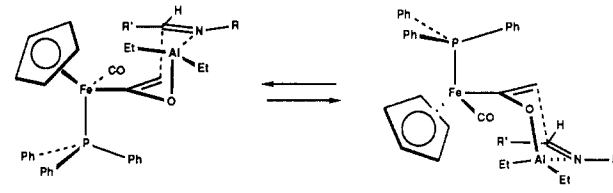


34

no reaction occurs from the syn enolate, **32**, in those reactions that are stereoselective. Since aldehydes are proposed to react stereoselectively from the anti enolate via a cyclic transition state when using an aluminum enolate,[17,24] we presume that imines are just as prone to follow that same reaction course. In support of this contention we point out that the slow imine condensation reactions were not affected by the amount of R$_2$AlCl used nor by the time allotted for counterion exchange prior to addition of the imine. If we apply the Davies–Seeman model to the imine reactions, we are led to consider chairlike transition state **33** for our imine condensations, but structure **33** alone is not fully consistent with our results. In particular, our attention was drawn to the results of entries 7–10 of Table IV, where the two imines derived from cinnamaldehyde reacted with significantly lower stereoselection than was observed for all of the other imines, while the two imines from α-methyl-substituted α,β-unsaturated aldehydes showed much improved diastereomer ratios (entries 7–10 of Table IV). If imines react *only* through the chairlike transition state **33**, we would expect no significant decrease in stereoselectivity for the α,β-unsaturated imines nor increase in stereoselection when a methyl group is introduced α to the imine on the double bond, because the model suggests that the R′ group of the imine is directed to the empty void above the CO ligand in structure **33**. The observation of significant control induced by the methyl group on the α carbon strongly suggests that the size of the R′ group on the *E* imine is intimately involved in a steric interaction that allows selection between *two* competing transition states. The requirement of two competing transition states and the presumption of a cyclic transition state to account for the imine results can be accommodated in one of two ways. Either we are seeing reaction through both a chairlike and a boatlike transition state, both of which retain the requirements of the Davies–Seeman model, or both the syn and the anti enolates are reactive which would preclude the use of the Davies–Seeman model for the imine reactions.

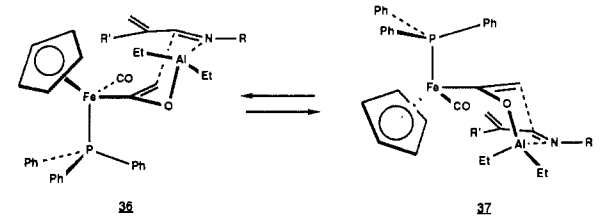
If the imine condensation reactions are occurring through both a chairlike transition state **33** and a boatlike transition state **34**, we cannot clearly rationalize the variation of stereoselection with the imine structure. Increasing the steric bulk of the imine R′ group would be expected to destabilize the boatlike transition state because of the increased 1,3-interactions between the imine R′ group and an ethyl group on the aluminum. However, the chairlike transition state would experience a similar destabilizing steric effect from the imine R′ group and an ethyl group on the aluminum.

We propose an alternative explanation of stereocontrol in the reaction of imines with the CpFe(PPh$_3$)(CO) system by returning to the simple model we originally proposed to account for the excellent stereoselection seen in the imine condensation.[12] Without considering the precise conformational preferences of the enolate of CpFe(PPh$_3$)(CO)COMe, we assume that all reactions of the enolate occur away from the very large PPh$_3$ ligand. By assuming that the poorly electrophilic imines require the reactivity enhancement provided by coordination to aluminum in a cyclic transition state and noting that aldimines exist exclusively in the *E* configuration under ambient conditions,[55] we are led to *two* simple chairlike transition states, **33** and **35**, that contain all of the features needed to explain our imine condensation results. The critical interactions take place between the imine R′ group and either the Cp ligand (structure **35**) or the CO ligand (structure **33**). In order to fully accommodate our results, we presume that



33 **35**

both enolates (O of enolate and CO syn and anti) are readily accessible and rapidly interconvert, and selective reaction through the less-hindered transition state, **33**, with the R′ group directed toward the CO ligand rationalizes the observed major product *and* explains the significant variation in the stereoselectivities noted for imines derived from the α,β-unsaturated aldehydes in Table IV. For example, the two imines derived from cinnamaldehyde reacted with significantly lower stereoselection than was observed for all of the other imines, while the two imines from α-methyl-substituted α,β-unsaturated aldehydes showed much improved diastereomer ratios (entries 7–10 of Table IV). Using transition states **36** and **37** for the α,β-unsaturated imines, we predict that the olefinic carbon α to the imine functional group would have a much smaller local steric demand than an analogous sp^3-hybridized center and should be less efficient at differentiating the two possible transition states. However, when the hydrogen on



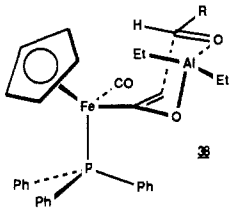
36 **37**

the sp^2 carbon is replaced by a methyl group, a larger substituent is directed back toward the Cp ligand and again the major product

(66) **Note Added in Proof.** After submission of this manuscript, the following articles from the Davies group appeared in our library: (a) Davies, S. G.; Easton, R. J. C.; Walker, J. C.; Warner, P. *J. Organomet. Chem.* **1985**, *296*, C40. (b) Davies, S. G.; Easton, R. J. C.; Walker, J. C.; Warner, P. *Tetrahedron* **1986**, *42*, 175. (c) Seeman, J. I.; Davies, S. G. *J. Am. Chem. Soc.* **1985**, *107*, 6522. (d) Davies, S. G.; Seeman, J. I.; Williams, I. H. *Tetrahedron Lett.* **1986**, 619. (e) Brown, S. L.; Davies, S. G.; Foster, D. F.; Seeman, J. I.; Warner, P. *Ibid.* **1986**, 623. (f) Davies, S. G.; Walker, J. C. *J. Chem. Soc., Chem. Commun.* **1986**, 495.

correlates with selective reaction through the less-hindered transition state (**36**). Further support that the important selection between transition state is dependent on the R′ group of the imine being directed toward the selectivity inducing chiral iron is found for the one cyclic imine tried in our studies (Table IV, entry 11) which showed very poor stereoselection. In this case a small vinyl hydrogen would be directed back toward the iron and its ligands, and using transition states **33** and **35** we would expect little or no stereoselection (1.3:1.0 ratio of diastereomers observed).

The peculiar requirement of 2 equiv of *n*-BuLi to achieve the excellent stereoselectivity in the aldol reaction of the aluminum enolate discovered by Davies requires comment. Since generation of the enolate with 1 equiv of *n*-BuLi or LDA followed by counterion exchange with Et_2AlCl only produced the moderate levels of stereoselection observed in our experiments, the size and complexity of the enolate counterion must have a significant influence on the stereochemical outcome of the aldol reaction. From Davies experiments with aldol condensations in the propanoyl iron system, it can be inferred that the aldol reaction occurs exclusively from the anti enolate (enolate O and CO anti), if one presumes that propanoyl iron system forms the *E* enolate exclusively and that the propanoyl iron complex accurately models the acetyl iron complex. If these reasonable presumptions are valid, we cannot use our analysis of reaction through syn and anti enolates to attempt to explain the aldol reactions and their sensitivity to equivalents of *n*-BuLi used to generate the enolate.[64] It is possible that the enolate steric bulk controls the distribution between the chairlike and boatlike transition states proposed earlier by Davies[17] (**38** and **39**) and that the high selectivity observed in the Davies aldol system is accounted for by the bulkier enolate counterion increasing the selectivity for the boatlike transition state because of increased steric interactions between the counterion and the Cp ring in the chair relative to the boat.



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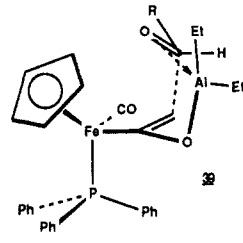
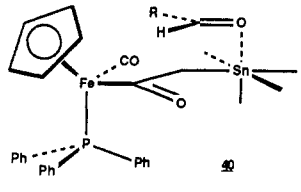


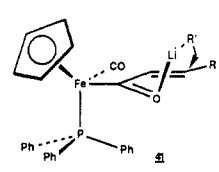
39

How can we explain the significant reversal of aldol stereoselection we observed when $SnCl_2$ was added to the lithium enolate prior to aldehyde addition? We are hesitant to overrationalize the tin results because they most likely are complicated by the presence of C-bonded enolates. Tin(IV) enolates exist as an equilibrating mixture of C- and O-bonded enolates significantly favoring the C-bonded structure,[56] and it is not unreasonable to expect the tin(II) system to behave similarly. However, if the tin enolate is reacting through a C-bonded structure, the results are consistent with an anti enolate model where the observed aldol stereochemistry is rationalized by minimizing the tin–Cp interaction and allowing the aldehyde to choose the orientation that places the R group away from the iron and its ligands (structure **40**).



40

The results of the conjugate addition/alkylation studies can be understood by applying the Davies anti enolate model to the alkylation portion of the two-step sequence and by presuming that delivery of the nucleophile in the conjugate addition to the enone is controlled by reaction through a six-membered-ring transition state with the lithium counterion coordinated to the acyl oxygen. We note that the correct product stereochemistry can be predicted by transition state **41**.[65] Indirect evidence for coordination of



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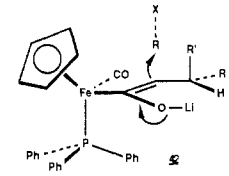
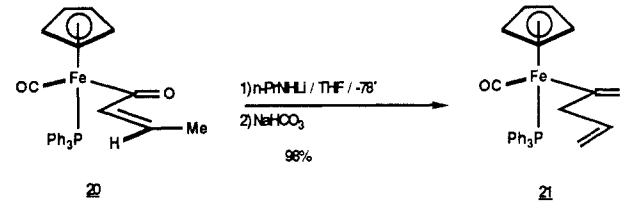


42

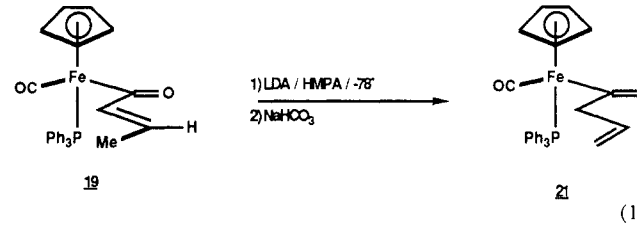
the lithium to the acyl oxygen will be given below. Because we routinely used 2 equiv of RLi or RNHLi for the conjugate addition step, we presume that the enolate formed when conjugate addition takes place will be similar to that produced by Davies in his deprotonations of η^5-CpFe(PPh$_3$)(CO)COR (R = Me and Et) with 2 equiv of *n*-BuLi. Accordingly, very high stereoselectivity is observed in the alkylation step, and the stereochemistry is consistent with alkylation through an anti enolate (structure **42**).

Why then are the results of the conjugate addition with MeLi (with or without LiBr) so anomalous? MeLi is unique among the simple organolithiums in its tendency to form very strong aggregates with itself, even in the presence of added donor ligands or coordinating solvents.[57] We suggest that for the case of conjugate addition of MeLi (at least 2 equiv was required for optimum yields) we have formed a very strong and somewhat bulky complex counterion containing at least one Li and one MeLi. If we generate an enolate counterion of sufficient bulk, steric interactions with the Cp ligand could become significant, leading to destabilizing of structure **42** relative to the syn enolate and resulting in diminished stereoselection. Consistent with this notion is the low stereoselection seen in the alkylation step with the cinnamyl iron system **22** when MeLi is conjugatively added followed by alkylation with MeI (see eq 12 and 13) and the typical high stereoselectivity regained when PhLi is used in place of MeLi (eq 15). These anomolous results with MeLi and the previously mentioned requirement of 2 equiv of *n*-BuLi for enolate generation in the Davies aldol chemistry together provide strong support for the importance of enolate counterions in all aspects of the iron acyl enolate chemistry.

Finally, we provide some evidence that the conjugate addition of RLi to the α,β-unsaturated iron acyls occurs through some type of prior coordination to the acyl oxygen. Our first hint of this requirement was obtained when we tried to add *n*-PrNHLi to the *Z* enone **20**, and after a protic workup we observed clean formation of the β,γ-unsaturated iron acyl **21** in 98% yield (eq 18). This

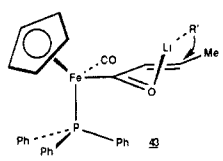


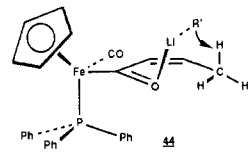
20 21 (18)



19 21 (19)

suggested to us that subtle geometric factors were controlling the outcome of this chemistry, and a reasonable hypothesis was that the organolithium reagent first coordinated to the acyl oxygen of the iron acyl and then delivered the nucleophile to the β-position of the enone in the case of the *E* enones (structure **43**), but removed a readily accessible γ-proton when reaction with the *Z* enone was attempted (structure **44**). If this hypothesis was correct, coordination of the organolithium reagent to the acyl oxygen of the *E* enone should be inhibited by the presence of a coordinating ligand such as hexamethylphosphoric triamide





(HMPA), and then deprotonation should then occur in the *E* enone system as well. Since lithium diisopropylamide (LDA) had been shown to add in a 1,4-fashion to the crotonyl system **19** (eq 11), we probed our hypothesis by adding HMPA to LDA prior to addition of enone **19**. Consistent with our hypothesis, deprotonation to the extended enolate occurred to the exclusion of conjugate addition (eq 19).

Conclusions

The results accumulated in this paper and in the various articles from the Davies group demonstrate the powerful influence that the chiral η^5-CpFe(PPh$_3$)(CO) group can have over the stereochemical outcome of reactions that occur under its control. Of what use might this chemistry be in synthesis? If, for the moment, we neglect the potential of the chiral iron system for absolute stereocontrol, the synthetic value can be seen in the function of the η^5-CpFe(PPh$_3$)(CO)COCH$_3$ group as a protected form of an acylium cation that can be liberated under fairly mild oxidizing conditions (Br_2 at −78 °C or I_2 at room temperature). The β-lactam synthesis described in this paper takes full advantage of this function of the iron acyl system. Additionally, the results described for the conjugate addition/alkylation reactions on the α,β-unsaturated iron acyls have demonstrated that extremely good control can be achieved on the relative stereochemistry of substituents introduced at the α and β positions of the organic carbonyl products.

Because the parent iron acetyl, η^5-CpFe(PPh$_3$)(CO)COCH$_3$, had been prepared in optically active form and is configurationally stable under ambient conditions, the use of one of the enantiomers of the iron acetyl in the chemistry described in this manuscript could provide access to organic substrates of very high enantiomeric purity. To be of practical value, however, an original method of synthesis of the optically active acyl will need to be found, because the literature method is not amenable to the simple preparation of large quantities of material. Furthermore, the value of the iron acyl system in controlling the stereochemistry of organic transformations will be in reactions that take advantage of the properties unique to the organotransition-metal nature of the system (such as the mild low temperature oxidative formation of β-lactams), not in reactions that simply mimic transformations achievable using traditional organic systems. Finally, it remains to be proven that an optically active iron acyl *enolate* will remain configurationally stable under the conditions of its generation and reactions.

Experimental Section

General. All infrared spectra were recorded on a Perkin-Elmer 1320 infrared spectrophotometer or a Perkin-Elmer 1420 ratio recording infrared spectrophotometer. The resolution of the 1320 was 3 cm^{-1} at 1000 cm^{-1} and 5 cm^{-1} at 3000 cm^{-1}. The resolution of the 1420 was 6 cm^{-1} from 4000 to 2000 cm^{-1} and 3 cm^{-1} from 2000 to 200 cm^{-1}. Nuclear magnetic resonance spectra were obtained at 60 MHz on a JEOL C-60 HL spectrometer, at 200 MHz on an IBM NB 200 SY FT spectrometer, at 270 MHz on a Bruker HX-270 and an IBM NB 270 SY FT spectrometer, and at 360 MHz on a Nicolet NMC-360 spectrometer. All NMR absorptions were expressed in parts per million (δ) relative to tetramethylsilane (Me_4Si) as an internal standard unless otherwise stated. Routine thin-layer chromatography was effected by using precoated 0.25-mm silica gel 60F-254 plates purchased from EM Reagents or precoated 0.20-mm aluminum oxide 60F-254 neutral Type E plates also purchased from EM Reagents. Routine gravity silica gel columns were performed on Baker (60–200-mesh) silica gel, and routine gravity alumina columns were performed on alumina purchased from Alcoa Chemicals (F-20, 60–200 mesh). Radial chromatography was done on a Model 7924 chromatotron from Harrison Research. Rotors were coated according to directions provided with either silica gel PF-254 with $CaSO_4 \cdot {}^1/_2H_2O$ Type 60 or aluminum oxide GF-254 Type E. Flash chromatographies were performed using Merck silica gel grade 60, 230–400 mesh, purchased from Aldrich Chemical Co. Melting points were determined on a Mel-Temp melting point apparatus or a Thomas Hoover capillary melting point apparatus and are reported uncorrected. Low-resolution electron-impact mass spectra were obtained on a Finnigan 4510 GC/MS system or a Varian M66 instrument. High-resolution mass spectra were obtained on an AEI MS 902. Combustion analyses were performed by Galbraith Laboratories, Inc. Tetrahydrofuran (THF), diethyl ether (Et_2O), and dimethoxyethane (DME) were all freshly distilled from sodium/benzophenone under nitrogen immediately prior to use. All reactions involving transition-metal organometallic complexes were performed under an atmosphere of dry nitrogen unless otherwise noted. The following chemicals were purchased from Aldrich and used as received: diisobutylaluminum chloride, chlorotitanium triisopropoxide, ethylaluminum dichloride, diethylaluminum chloride, triethylaluminum, titanium trichloride, magnesium bromide etherate, and cyclopentadienyliron dicarbonyl dimer. The following were purchased from Alfa and used as received: tin(II) bromide, tin(II) iodide, and bis(cyclopentadienyl)zirconium dichloride. Tin(II) chloride hydrate was purchased from Mallinckrodt and dried before use. All alkylating agents were used as received from Aldrich, unless discoloration indicated they should be distilled prior to use. All alkylaldehydes were used as received from Aldrich except pivaldehyde which was synthesized according to known procedures.[58] Other aldehydes which were discolored (PhCHO, acrolein, and cinnamaldehyde) were distilled prior to use. All imines were synthesized according to standard procedures.[59] One of two procedures was routinely used depending on the reactivity of the aldehyde. Reactive aldehydes could be stirred neat or in water with the amine, followed by KOH saturation of the aqueous layer and distillation of the imine. In cases where imine formation was slow, a CH_2Cl_2 solution of the amine, which contained $MgSO_4$, was cooled to 0 °C, and the aldehyde was added slowly to this solution. The solution was then stirred for several hours followed by solvent removal and distillation or recrystallization of the imine. Boiling points and spectral data for a variety of imines can be found in ref 60. The unsubstituted thiazoline and oxazoline were synthesized according to procedures found in ref 61. All nitrones used were synthesized according to standard procedures (acyclic nitrones[62] and cyclic nitrones[63]).

Typical Procedure for the Alkylation or Aldol Reaction of Lithium Enolate (2). Diisopropylamine (0.19 mL, 1.36 mmol) was added to a solution of *n*-BuLi (0.825 mL of a 1.6 M solution in hexanes, 1.32 mmol) in 8 mL of THF maintained at 0 °C for 20 min. The solution was then cooled to −42 °C, and iron acyl **1** (500 mg, 1.10 mmol) in 4 mL of THF was added by syringe. The initial orange of the acyl turned to deep red. The solution was stirred at −42 °C for 90 min, and then the enolate was quenched by the addition of benzyl bromide (0.170 mL, 1.43 mmol) which caused an immediate color change from red to dark orange. The reaction mixture was allowed to warm to room temperature, and after 30 min aqueous NH_4Cl (5%, 30 mL) was added. The aqueous layer was extracted with CH_2Cl_2 (3 × 30 mL), the organic extracts dried (Na_2SO_4), and the solvent removed by rotary evaporation to yield an orange oil that was chromatographed on alumina (Alcoa F-20, 60–200 mesh, 2 × 5 cm, CH_2Cl_2) to yield 542 mg (91%) of iron complex **3** (R = CH_2Ph) as an orange solid. As a general rule, alkylation products had a higher R_f than the starting material **1**, and aldol products had a lower R_f than the starting material. In most cases, small amounts of unreacted starting acyl complex were recovered. **3**, R = CH_2Ph: mp 128–131 °C (CH_2Cl_2/petroleum ether); IR ($CHCl_3$, cm^{-1}) 3050, 3010, 1920, 1600, 1490, 1440, 1100, 830; ^{1}H NMR ($CDCl_3$) 7.6–6.8 (m, 20 H), 4.3 (d, J = 2 Hz, 5 H), 3.2–2.0 (m, 4 H). Anal. Calcd for $C_{33}H_{29}O_2PFe$: C, 72.81; H, 5.37. Found: C, 72.89; H, 5.55.

The following alkylation and aldol products were synthesized analogously. **3**, R = Me, 91%: orange solid; mp 158–161 °C ($CHCl_3$/petroleum ether); IR ($CHCl_3$, cm^{-1}) 3040, 3010, 2980, 1910, 1605, 1490, 1440, 1100, 1080, 880, 830; ^{1}H NMR ($CDCl_3$) 7.50–7.13 (m, 15 H), 4.33 (br s, 5 H), 2.93–2.37 (m, 2 H), 0.56 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{27}H_{25}O_2PFe$: C, 69.25; H, 5.38. Found: C, 69.47; H, 5.48. **3**, R = Et; 81%: orange solid; mp 157–159 °C ($CHCl_3$/petroleum ether); IR ($CHCl_3$, cm^{-1}) 3020, 2980, 1920, 1608, 1440, 1100; ^{1}H NMR ($CDCl_3$) 7.50–7.13 (m, 15 H), 4.35 (br s, 5 H), 2.93–2.40 (m, 2 H), 1.43–0.87 (m, 2 H), 0.58 (t, J = 6 Hz, 3 H). Anal. Calcd for $C_{28}H_{27}O_2PFe$: C, 69.72; H, 5.64. Found: C, 69.82; H, 5.80. **3**, R = allyl; 78%: orange solid; mp 115–117 °C ($CHCl_3$, petroleum ether); IR ($CHCl_3$, cm^{-1}) 3040, 3005, 1910, 1600, 1485, 1440, 1100, 910, 820; ^{1}H NMR ($CDCl_3$) 7.40–7.03 (m, 15 H), 5.70–5.07 (m, 1 H), 4.93–4.50 (m, 2 H), 4.30 (br s, 5 H), 3.00–2.47 (m, 2 H), 2.10–1.57 (m, 2 H). Anal. Calcd for $C_{29}H_{27}O_2PFe$: C, 70.46; H, 5.51. Found: C, 70.36; H, 5.73.

Aldol Products (5/6) (in Equation 3). R = R′ = Me, 71%: yellow-orange solid; mp 130–132 °C ($CHCl_3$/petroleum ether); IR ($CHCl_3$, cm^{-1}) 3420, 3080, 2995, 1920, 1590, 1490, 1440, 1120, 1100, 950; ^{1}H NMR ($CDCl_3$) 7.67–7.10 (m, 15 H), 4.30 (d, J = 1 Hz, 5 H), 4.00 (br

s, 1 H), 3.17 (d, J = 17 Hz, 1 H), 2.70 (d, J = 17 Hz, 1 H), 1.00 (s, 3 H), 0.70 (s, 3 H). Anal. Calcd for $C_{29}H_{29}O_3PFe$: C, 67.98; H, 5.71. Found: C, 67.70; H, 5.69. R, R′ = t-Bu, H, 69% (50/50 mixture of diastereomers): yellow-orange solid; IR ($CHCl_3$, cm^{-1}) 3440, 3080, 3020, 2980, 1920, 1585, 1480, 1440, 1095, 1070, 1000, 825; ^1H NMR ($CDCl_3$) 7.50–6.93 (m, 15 H), 4.23 (br s, 5 H), 3.60–2.50 (complex m, 3 H), 2.13 (br s, 1 H), 0.63, 0.60 (two singlets, 9 H total, 50/50 ratio). Anal. Calcd for $C_{31}H_{33}O_3PFe$: C, 68.80; H, 6.16. Found: C, 68.97; H, 5.90. Complexes **5/6**, (R, R′ = Me, H; 93% and R, R′ = Ph, H, 84%) were also synthesized analogously; however, the spectral data for these compounds are included in the aldol condensation counterion change experimental section.

Typical Procedure for Oxidative Cleavage of the Iron Acyl. Cleavage of the metal–acyl bond was effected by dissolving iron complex **3** (R = CH_2Ph) (389 mg, 0.715 mmol) in 5 mL of CH_2Cl_2 and diluting with an equal volume of EtOH. This solution was cooled to −42 °C, and N-bromosuccinimide (142 mg, 0.793 mmol) dissolved in 5 mL of CH_2Cl_2 was added dropwise. The color of the solution slowly changed from orange to deep green. After the addition, the solution was allowed to warm to room temperature and after 45 min was transferred to a separatory funnel with the aid of CH_2Cl_2 and then washed with 1 N aqueous NaOH. After the aqueous solution was back extracted with CH_2Cl_2, the combined organic extracts were dried over Na_2SO_4. Filtration followed by solvent removal on a rotary evaporator left a crude green product that was triturated with several small portions of ether. The combined ether fractions were condensed to an oil and filtered through a short alumina (Alcoa-F20, 60–200-mesh) column with petroleum ether to remove traces of the green η^5-CpFe(PPh_3)(CO)I and to yield ethyl dihydrocinnamate (114 mg, 89%) identical with an authentic sample: IR (CH_2Cl_2, cm^{-1}), 1722; ^1H NMR ($CDCl_3$) 7.11 (m, 5 H), 4.05 (q, J = 7 Hz, 2 H), 2.73 (m, 4 H), 1.18 (t, J = 7 Hz, 3 H).

Counterion Variations in Aldol Condensations of Iron Acetyl 1 (Tables I and II). Lithium diisopropylamide was generated from n-BuLi (0.41 mL of a 1.6 M solution in hexanes, 0.66 mmol) and diisopropylamine (0.090 mL, 0.66 mmol) stirred together in 6 mL of THF for 15 min at 0 °C and then cooled to −42 °C. Iron acetyl **1** (200 mg, 0.44 mmol) in 2 mL of THF was added slowly to the LDA, and the deep red enolate solution generated was stirred for 1 h at −42 °C. The solution was then cooled to −78 °C and diisobutylaluminum chloride (0.565 mL of a 1.24 M solution in hexane, 0.70 mmol) was added. The color of the solution went from deep red to a deep yellow–brown (some lightening of enolate color occurred with all counterions used). This solution was stirred for 15 min at −78 °C, then isobutyraldehyde (0.080 mL in 0.50 mL of THF, 0.88 mmol) was added, and the color went rapidly to brown and then yellow. The solution was stirred for an additional 3 h at −78 °C followed by quenching at that temperature with 3 mL of a saturated aqueous $NaHCO_3$ solution. The solution was then allowed to warm to room temperature, and an additional 20 mL of this aqueous base was added. The usual extraction (CH_2Cl_2, 3 × 20 mL), drying (Na_2SO_4), and solvent removal by rotary evaporation yielded a crude orange-yellow solid that was chromatographed on alumina with CH_2Cl_2 (Alcoa F-20, 60–200 mesh, 2 × 20 cm) to yield unreacted starting material **1** (13.5 mg, 7%) followed by elution with EtOH to yield the desired aldol products **5/6** (R = i-Pr; yellow solid, 176.3 mg, 76%) as a mixture of diastereomers (**5**:**6**, 1.0:8.2): IR ($CHCl_3$, cm^{-1}) 3420, 3070, 3005, 2975, 2884, 1918, 1580, 1485, 1438, 1125, 1097, 1003, 942, 829; ^1H NMR (C_6D_6) (major) 7.78–7.49 (m, 6 H), 7.22–6.89 (m, 9 H), 4.22 (d, J = 1 Hz, 5 H), 3.80 (d, J = 2 Hz, 1 H), 3.25 (m, 2 H), 3.04 (dd, J = 17, 10 Hz, 1 H), 1.60 (m, 1 H), 1.04 (d, J = 6 Hz, 3 H), 0.96 (d, J = 6 Hz, 3 H); ^1H NMR (minor; minor diastereomer here was the major diastereomer isolated from an analogous Sn enolate; resonances distinguishable from those above are reported) 4.26 (d, J = 1 Hz, 5 H), 3.87 (m, 1 H), 3.41 (dd, J = 18, 2 Hz, 1 H), 3.29 (d, J = 2 Hz, 1 H), 2.78 (dd, J = 18, 9 Hz, 1 H), 1.02 (d, J = 6 Hz, 3 H), 0.98 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{30}H_{31}O_3PFe$: C, 68.45; H, 5.94. Found: C, 68.68; H, 5.93. **5/6**, R = E—CH=CHPr, 82% (1.0:2.5 mixture of diastereomers): yellow-orange solid; IR ($CHCl_3$, cm^{-1}) 3410, 3068, 3005, 2970, 2939, 2880, 1920, 1582, 1485, 1438, 1178, 1121, 1096, 1001, 973, 828; ^1H NMR (C_6D_6) (major) 7.78–7.56 (m, 6 H), 7.20–6.93 (m, 9 H), 5.78 (m, 1 H), 5.49 (dd, J = 16, 5 Hz, 1 H), 4.19 (m, br, 1 H), 4.22 (d, J = 1 Hz, 5 H), 3.97 (d, J = 3 Hz, 1 H), 3.23 (s, br, 1 H), 3.20 (s, br, 1 H), 1.93 (m, 2 H), 1.31 (m, 2 H), 0.85 (t, J = 6 Hz, 3 H); ^1H NMR (minor; minor diastereomer here was the major diastereomer isolated from an analogous Sn enolate; resonances distinguishable from those above are reported) 4.62 (m, br, 1 H), 4.20 (d, J = 1 Hz, 5 H), 3.48 (dd, J = 17, 2.5 Hz, 1 H), 3.40 (d, J = 2 Hz, 1 H), 3.01 (dd, J = 17, 10 Hz, 1 H), 0.82 (t, J = 6 Hz, 3 H). Anal. Calcd for $C_{32}H_{33}O_3PFe$: C, 69.57; H, 6.02. Found: C, 69.83; H, 6.22. **5/6**, R = CH=CHPh, 68% (1.0:1.7 mixture of diastereomers): yellow-orange solid; IR ($CHCl_3$, cm^{-1}) 3405, 3090, 3068, 3010, 1922, 1586, 1488, 1439, 1180, 1124, 1098, 1003, 971, 829; ^1H NMR (C_6D_6) (major) 7.77–7.56 (m, 6 H), 7.34–6.95 (m, 9 H), 6.83 (d, J = 15 Hz, 1 H), 6.17 (dd, J = 15, 5 Hz, 1 H), 4.34 (m, br, 1 H), 4.22 (d, J = 1 Hz, 5 H), 4.06 (d, J = 2 Hz, 1 H), 3.27 (s, br, 1 H), 3.24 (s, br, 1 H); ^1H NMR (minor; minor diastereomer here was the major diastereomer isolated from an analogous Sn enolate; resonances distinguishable from those above are reported) 6.80 (d, J = 15 Hz, 1 H), 6.18 (dd, J = 15, 5 Hz, 1 H), 4.77 (m, br, 1 H), 4.22 (d, J = 1 Hz, 5 H), 3.55 (d, br, J = 3 Hz, 1.5 H, with adjacent 3.48 (d, J = 2.5 Hz, 0.5 H), 2 H total), 3.07 (dd, J = 18, 9 Hz, 1 H). Anal. Calcd for $C_{35}H_{31}O_3PFe$: C, 71.68; H, 5.33. Found: C, 71.41; H, 5.33. **5/6**, R = Ph, 81% (1.0:3.5 mixture of diastereomers): yellow-orange solid; IR ($CHCl_3$, cm^{-1}) 3407, 3059, 3000, 1919, 1580, 1480, 1434, 1093, 998, 937, 824; ^1H NMR (major) 7.78–7.56 (m, 6 H), 7.47 (m, 2 H), 7.29–6.93 (m, 12 H), 4.69 (d, br, J = 9 Hz, 1 H), 4.44 (d, J = 2 Hz, 1 H), 4.11 (d, J = 1 Hz, 5 H), 3.40 (dd, J = 18, 2 Hz, 1 H), 3.31 (dd, J = 18, 9 Hz, 1 H); ^1H NMR (minor; minor diastereomer here was the major diastereomer from an analogous Sn enolate; resonances distinguishable from those above are reported) 5.22 (d, br, J = 9 Hz, 1 H), 4.20 (d, J = 1 Hz, 5 H), 3.69 (d, br, J = 2 Hz, 1.5 H, with adjacent 3.62 (d, J = 2 Hz, 0.5 H), 2 H total), 3.09 (dd, J = 18, 9 Hz, 1 H). Anal. Calcd for $C_{33}H_{29}O_3PFe$: C, 70.73; H, 5.22. Found: C, 71.00; H, 5.24. **5/6**, R = Me, 60% from Sn (5.4:1.0 mixture of diastereomers): yellow-orange solid; IR ($CHCl_3$, cm^{-1}) 3395, 3078, 3060, 2998, 1918, 1583, 1481, 1435, 1120, 1093, 965, 825; ^1H NMR (C_6D_6) (major from Sn) 7.78–7.56 (m, 6 H), 7.20–6.93 (m, 9 H), 4.21 (d, J = 1 Hz, 5 H), 4.17 (m, 1 H), 3.40 (m, br, 1.5 Hz, with adjacent 3.32 (d, J = 2 Hz, 0.5 H), 2 H total), 2.84 (dd, J = 18, 9 Hz, 1 H), 1.06 (d, J = 6 Hz, 3 H); ^1H NMR (minor from Sn; resonances distinguishable from those above are reported) 4.23 (d, J = 1 Hz, 5 H), 3.20 (dd, J = 18, 2 Hz, 1 H), 3.00 (dd, J = 18, 9 Hz, 1 H), 1.04 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{28}H_{27}O_3PFe$: C, 67.49; H, 5.46. Found: C, 67.70; H, 5.66. **5/6**, R = Et, 73% (1.0:5.2 mixture of diastereomers): yellow-orange solid; IR ($CHCl_3$, cm^{-1}) 3440, 3065, 3009, 2976, 2942, 2890, 1918, 1585, 1484, 1438, 1135, 1093, 1019, 1002, 975, 931, 829; ^1H NMR (C_6D_6) (major) 7.78–7.49 (m, 6 H), 7.22–6.89 (m, 9 H), 4.21 (d, J = 1 Hz, 5 H), 3.78 (d, J = 2 Hz, 1 H), 3.41 (m, br, 1 H), 3.21 (dd, J = 18, 2 Hz, 1 H), 3.02 (dd, J = 18, 9 Hz, 1 H), 1.38 (m, 2 H), 0.98 (t, J = 7 Hz, 3 H); ^1H NMR (minor; minor diastereomer here was the major diastereomer isolated from an analogous Sn enolate; resonances distinguisable from those above are reported) 4.23 (d, J = 1 Hz, 5 H), 3.96 (m, br, 1 H), 3.38 (dd, J = 18, 2 Hz, 1 H), 3.29 (d, J = 2 Hz, 1 H), 2.84 (dd, J = 18, 9 Hz, 1 H), 1.00 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{29}H_{29}O_3PFe$: C, 67.98; H, 5.71. Found: C, 68.12; H, 5.90.

Specific comments about procedures for the other counterions used are included below: Diethylaluminum chloride and chlorotitanium triisopropoxide were used as received as 1.0 M solutions in hexanes. $SnCl_2$ was prepared from the dihydrate and a freshly prepared 0.25 M solution in THF was used for best results. Magnesium bromide etherate was used as a freshly prepared 0.25 M solution in THF. Diisobutylaluminum chloride was used as received as a 25% wt/wt solution in hexanes. Isobutylaluminum dichloride was used as received as a 25% wt/wt solution in hexanes. $Sn(OTf)_2$ was freshly prepared and used as a freshly prepared 0.5 M solution in THF. Cp_2ZrCl_2 was used as a freshly prepared THF solution. $SnBr_2$ and SnI_2 were used as freshly prepared THF solutions.

Condensation of Lithium Enolate 2 with PhCH=NPh. Lithium diisopropylamide was generated from diisopropylamine (0.111 mL, 0.793 mmol) and n-BuLi (0.495 mL of a 1.6 M solution in hexanes, 0.793 mmol) stirred together for 15 min at 0 °C and then cooled to −42 °C. Iron acetyl **1** (300 mg, 0.661 mmol) in 2 mL of THF was added to this solution slowly. This generated the usual deep red enolate solution that was stirred for 45 min at −42 °C. Benzylideneaniline (140 mg, 0.772 mmol) was dissolved in 1 mL of THF and added slowly to this solution. The deep red solution slowly changed to deep orange over the course of 1 h. The reaction was then quenched by the addition of 10 mL of a saturated aqueous $NaHCO_3$ solution at −42 °C. The solution was allowed to warm to room temperature, and an additional 20 mL of aqueous $NaHCO_3$ was added (if 5% NH_4Cl was used to quench the reaction, the protonated amine form of the iron complex was isolated). The aqueous layer was extracted (3 × 20 mL) (CH_2Cl_2), the extracts were dried (Na_2SO_4), and the solvent was removed by rotary evaporating and pumping under vacuum. The resulting orange solid was triturated with several portions of ether to separate the major product diastereomer **7** (R = Ph) (insoluble) from the minor product diastereomer **8** (R = Ph). This separation yielded 304.2 mg (72%e of purified major diastereomer and 66 mg of an orange ether soluble solid that contained the minor diastereomer (53.5 mg, 13%) in addition to starting material **1** (2%) and unsaturated cinnamyl iron complex **22** (1%). Major diastereomer **7**: mp 173–174 °C (CH_2Cl_2/Et_2O); IR ($CHCl_3$, cm^{-1}) 3072, 3018, 1915, 1598, 1502, 1435, 1313, 1094, 1002, 970, 918, 826; ^1H NMR ($CDCl_3$)

7.58–7.11 (m, 15 H), 7.02 (t, J = 8 Hz, 2 H), 6.59 (t, J = 8 Hz, 1 H), 6.35 (d, J = 8 Hz, 2 H), 4.67 (s, br, 1 H), 4.31 (d, J = 1 Hz, 5 H, with an underlying 1 H multiplet absorption), 3.39 (dd, J = 16, 8 Hz, 1 H), 2.91 (dd, J = 16, 3 Hz, 1 H). Anal. Calcd for $C_{39}H_{34}NO_2PFe$: C, 73.71; H, 5.39; N, 2.20. Found: C, 73.81; H, 5.43; N, 2.18. Minor diastereomer **8** (R = Ph): mp 171–172 °C (ether); IR ($CHCl_3$, cm^{-1}) 3071, 3016, 2942, 2870, 1916, 1600, 1501, 1437, 1316, 1095, 1000, 969, 827; ^{1}H NMR ($CDCl_3$) 7.58–7.11 (m, 15 H), 7.04 (t, J = 8 Hz, 2 H), 6.60 (t, J = 8 Hz, 1 H), 6.37 (d, J = 8 Hz, 2 H), 4.68 (dd, J = 10, 4 Hz, 1 H), 4.34 (d, J = 1 Hz, 5 H), 3.18 (dd, J = 15, 4 Hz, 1 H), 2.49 (dd, J = 15, 10 Hz, 1 H); mass spectrum, m/e 635.1 (M$^+$). If the above reaction was allowed to warm to 0 °C before quenching, then the **7**:**8** ratio decreased to 2:1 (64%), and 24% of the elimination product **22** was isolated: mp 122.5–124.5 °C (ether); IR ($CHCl_3$, cm^{-1}) 3079, 3018, 2960, 1919, 1619, 1581, 1551, 1489, 1442, 1319, 1192, 1128, 1098, 1037, 1020, 979, 917, 893, 851, 832; ^{1}H NMR ($CDCl_3$) 7.88–7.13 (m, 20 H), 7.08 (d, J = 16 Hz, 1 H), 6.13 (d, J = 16 Hz, 1 H), 4.47 (d, J = 1 Hz, 5 H); mass spectrum, m/e 542.4 (M$^+$). When the same imine condensation reaction was attempted with the aluminum enolate described in the following section, and if the reaction was allowed to warm to room temperature before quenching, the cinnamyl iron acyl **22** could be isolated in 69% yield.

Typical Experimental Procedure for the Condensation of Aluminum Enolate 2 with Imines. Lithium diisopropylamide and the lithium enolate of complex **1** were generated exactly as outlined in the procedure above. Diethylaluminum chloride (1.5 mL of a 1.0 M solution in hexanes, 1.5 mmol) was added by syringe, and the deep red only lightens slightly to a deep red-orange. Typically, 1.2–1.5 equiv of diethylaluminum chloride can be used with little change in the product yield. The solution was stirred for 15 min at −42 °C after the addition of Et_2AlCl and then benzylidene-*n*-propylamine (117 mg, 0.79 mmol) in 1 mL of THF was added slowly. The color of the reaction mixture slowly lightened to orange after the imine was added. After 3 h at −42 °C the reaction was quenched with saturated aqueous $NaHCO_3$ (3 mL). The solution was warmed to room temperature, and an additional 20 mL of this aqueous base was added. The aqueous layer was extracted with CH_2Cl_2 (3 × 20 mL); the CH_2Cl_2 extracts were combined and then dried over $MgSO_4$. Removal of solvent on a rotary evaporator left an orange oil that was chromatographed on silical gel (60–200 mesh, 2 × 20 cm), eluting with CH_2Cl_2 and then ether (in most cases there were significant amounts of starting complex **1** recovered through CH_2Cl_2 elution) to yield 319 mg (80%) of the desired β-amino acyl complex **7** (R = *n*-Pr, R′ = Ph) as an orange solid: mp 143–145 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3073, 3013, 2984, 1918, 1591, 1484, 1438, 1352, 1094, 1072, 933, 826; ^{1}H NMR ($CDCl_3$) 7.73–7.07 (m, 20 H), 4.41 (d, J = 1 Hz, 5 H), 3.47 (dd, J = 10, 2 Hz, 1 H), 3.26 (dd, J = 18, 10 Hz, 1 H), 2.84 (dd, J = 18, 2 Hz, 1 H), 2.16 (m, 2 H), 1.36 (m, 2 H), 0.79 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{36}H_{36}NO_2PFe$: C, 71.89; H, 6.03; N, 2.33. Found: C, 72.00; H, 6.13; N, 2.24. Complex **7** (R = *n*-Pr, R′ = *i*-Pr; 68%) was synthesized analogously: mp 95–97 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3073, 2984, 2882, 1916, 1593, 1482, 1438, 1121, 1094, 1068, 1035, 916, 827; ^{1}H NMR ($CDCl_3$) 7.78–7.11 (m, 15 H), 4.44 (d, J = 1 Hz, 5 H), 3.00 (dd, J = 18, 8 Hz, 1 H), 2.67 (dd, J = 18, 3 Hz, 1 H), 2.51–2.29 (m, 3 H), 1.16–1.04 (m, 3 H), 0.89 (t, J = 7 Hz, 3 H), 0.71 (d, J = 6 Hz, 3 H), 0.62 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{33}H_{38}NO_2PFe$: C, 69.84; H, 6.75; N, 2.47. Found: C, 70.01; H, 6.71; N, 2.21. Complex **7** (R = C_6H_{11}, R′ = Ph; 54%) was synthesized analogously: mp 154–155 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3074, 3022, 2950, 2872, 1920, 1597, 1485, 1454, 1440, 1094, 1002, 932, 830; ^{1}H NMR ($CDCl_3$) 7.78–6.98 (m, 20 H), 4.40 (d, J = 1 Hz, 5 H), 3.71 (dd, J = 9, 2.5 Hz, 1 H), 3.22 (dd, J = 18, 9 Hz, 1 H), 2.76 (dd, J = 18, 2.5 Hz, 1 H), 2.13–0.78 (m, 11 H). Anal. Calcd for $C_{39}H_{40}NO_2PFe$: C, 73.01; H, 6.28; N, 2.18. Found: C, 72.91f H, 6.34; N, 2.07. Complex **7** (R = C_6H_{11}, R′ = *i*-Pr; 57%) was synthesized analogously: mp 116–119 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3077, 2952, 2875, 1917, 1594, 1488, 1440, 1124, 1097, 918, 830; ^{1}H NMR (C_6D_6) 7.85–7.58 (m, 5 H), 7.11–6.93 (m, 10 H), 4.33 (d, J = 1 Hz, 5 H), 3.32 (dd, J = 18, 8 Hz, 1 H), 2.95 (m, 2 H), 2.48 (m, 1 H), 1.96–1.01 (m, 1 H), 0.98 (d, J = 7 Hz, 3 H), 0.81 (d, J = 7 Hz, 3 H). Anal. Calcd for $C_{36}H_{42}NO_2PFe$: C, 71.70; H, 6.97; N, 2.31. Found: C, 71.57; H, 6.79; N, 2.16. Complex **7**/**8**, R = anisyl, R′ = CH=CHPh, 68% (1.3:1.0 mixture of diastereomers): IR ($CHCl_3$, cm^{-1}) 3072, 3012, 2972, 2853, 1911, 1597, 1507, 1483, 1436, 1237, 1182, 1093, 1040, 1001, 980, 919, 822; ^{1}H NMR ($CDCl_3$; the following absorptions were readily distinguished) (major) 6.36 (d, J = 15 Hz, 1 H), 5.98 (dd, J = 15, 6 Hz, 1 H), 4.36 (d, J = 1 Hz, 5 H), 3.85 (m, 1 H), 3.68 (s, 3 H), 3.22 (dd, J = 15, 4.5 Hz, 1 H), 2.59 (dd, J = 15, 7.5 Hz, 1 H); ^{1}H NMR (minor) 6.06 (dd, J = 15, 6 Hz, 1 H), 4.38 (d, J = 1 Hz, 5 H), 4.09 (m, 1 H), 3.69 (s, 3 H), 3.34 (dd, J = 17, 7 Hz, 1 H), 2.85 (dd, J = 17, 4.5 Hz, 1 H). Anal. Calcd for $C_{42}H_{38}NO_3PFe$: C, 72.94; H, 5.54; N, 2.03. Found: C, 73.04; H, 5.61; N, 1.94. Complex **7**/**8**, R = *n*-Pr, R′ = CH=CHPh, 44% (2.5:1.0 mixture of diastereomers): IR ($CHCl_3$, cm^{-1}) 3071, 3011, 2972, 2946, 2890, 1912, 1590, 1481, 1434, 1386, 1351, 1308, 1178, 1121, 1092, 1002, 969, 922, 843, 823; ^{1}H NMR ($CDCl_3$; the following absorptions were readily distinguished) (major) 6.20 (d, J = 16 Hz, 1 H), 5.83 (dd, J = 16, 8 Hz, 1 H), 4.47 (d, J = 1 Hz, 5 H), 3.19 (dd, J = 18, 9 Hz, 1 H), 3.08 (dd, J = 9, 2 Hz, 1 H), 2.75 (dd, J = 18, 2 Hz, 1 H), 0.87 (t, J = 7 Hz, 3 H); ^{1}H NMR (minor) 6.39 (d, J = 16 Hz, 1 H), 5.96 (dd, J = 16, 8 Hz, 1 H), 4.42 (d, J = 1 Hz, 5 H), 2.94 (dd, J = 17, 8 Hz, 1 H), 0.81 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{38}H_{38}NO_2PFe$: C, 72.73; H, 6.10; N, 2.23. Found: C, 72.91; H, 6.16; N, 2.14. Complex **7** (R = *n*-Pr, R′ = CMe=CHPh; 53%) was synthesized analogously: mp 139–141 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3073, 2984, 1915, 1587, 1483, 1438, 1384, 1094, 1073, 1032, 1003, 926, 826; ^{1}H NMR ($CDCl_3$) 7.76–7.09 (m, 20 H), 6.17 (s, br, 1 H), 4.44 (d, J = 1 Hz, 5 H), 3.19 (dd, J = 17, 10 Hz, 1 H), 3.00 (d, J = 10 Hz, 1 H), 2.70 (d, J = 17 Hz, 1 H), 2.29 (t, J = 7 Hz, 2 H), 1.68 (d, J = 1 Hz, 3 H), 1.42 (m, 2 H), 0.86 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{39}H_{40}NO_2PFe$: C, 73.01; H, 6.28; N, 2.18. Found: C, 73.07; H, 6.33; N, 2.06. Complex **7** (R = *n*-Pr, R′ = CMe=CHEt; 37%) was synthesized analogously: mp 137–139 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3076, 2981, 2951, 2892, 1918, 1594, 1485, 1464, 1439, 1097, 931, 828; ^{1}H NMR ($CDCl_3$) 7.54–7.27 (m, 15 H), 5.02 (t, br, J = 6 Hz, 1 H), 4.42 (d, J = 1 Hz, 5 H), 3.07 (dd, J = 17, 10 Hz, 1 H), 2.84 (dd, J = 10, 3 Hz, 1 H), 2.62 (dd, J = 17, 3 Hz, 1 H), 2.21 (t, br, J = 8 Hz, 3 H), 1.96 (m, 2 H), 1.40 (s, br, 3 H), 1.38 (m, 2 H), 0.93 (t, J = 8 Hz, 3 H), 0.85 (t, J = 8 Hz, 3 H). Anal. Calcd for $C_{35}H_{40}NO_2PFe$: C, 70.83; H, 6.79; N, 2.36. Found: C, 70.70; H, 6.61; N, 2.27. Compound **7** (R = CH_2Ph, R′ = Et; 36%) was synthesized analogously: mp 68–70 °C (CH_2Cl_2/ether); IR ($CHCl_3$, cm^{-1}) 3073, 3011, 2979, 2943, 2888, 1912, 1592, 1482, 1457, 1435, 1094, 1000, 916, 824; ^{1}H NMR ($CDCl_3$) 7.57–7.14 (m, 20 H), 4.39 (d, J = 1 Hz, 5 H), 3.64 (d, J = 12 Hz, 1 H), 3.54 (d, J = 12 Hz, 1 H), 3.08 (dd, J = 17, 7 Hz, 1 H), 2.72 (dd, J = 17, 4.5 Hz, 1 H), 2.54 (m, 1 H), 1.08 (m, 2 H), 0.72 (t, J = 8 Hz, 3 H). Anal. Calcd for $C_{36}H_{36}NO_2PFe$: C, 71.89; H, 5.98; N, 2.33. Found: C, 71.93; H, 6.10; N, 2.25. Complex **7** (R = CH_2Ph, R′ = Ph; 75%) was synthesized analogously: mp 148–149 °C (ether); IR (CH_2Cl_2, cm^{-1}) 3079, 3062, 3036, 2963, 2931, 2895, 2836, 1916, 1599, 1479, 1451, 1432, 1390, 1348, 1307, 1198, 1114, 1092, 1028, 999, 930, 908, 843, 826, 688, 611; ^{1}H NMR (C_6D_6) 7.78–6.78 (m, 25 H), 4.15 (d, J = 1 Hz, 5 H), 3.89 (dd, J = 10, 2.5 Hz, 1 H), 3.65 (d, J = 13 Hz, 1 H), 3.56 (dd, J = 16, 10 Hz, 1 H), 3.52 (d, J = 13 Hz, 1 H), 3.31 (dd, J = 16, 2.5 Hz, 1 H). Anal. Calcd for $C_{40}H_{36}NO_2PFe$: C, 73.96; H, 5.59; N, 2.17. Found: C, 73.76;f H, 5.58; N, 1.99. Complex **7**/**8** (R, R′ → 5,5-dimethyl-1-proline; 80%) was also synthesized analogously. This complex (mixture of diastereomers) showed spectral properties identical with the complex synthesized from condensation/reductive N–O cleavage with cyclic nitrone **10** reported bellow.

Condensation of 2 with PhCH=N(O)Ph. Preparation of Hydroxyamine Iron Complex 9. Lithium diisopropylamide (LDA) was generated from *n*-BuLi (1.03 mL of a 1.6 M solution in hexanes, 1.65 mmol) and diisopropylamine (0.275 mL, 1.65 mmol) in 5 mL of THF at −42 °C for 30 min. Iron acetyl **1** (500 mg, 1.1 mmol) was dissolved in 3 mL of THF and added dropwise to the LDA to generate the deep-red enolate, which was stirred for 1 h at −42 °C. The flask was then cooled to −78 °C, diisobutylaluminum chloride (1.33 mL of a 1.24 M solution in hexanes, 1.65 mmol) was added, and the solution turned a deeper red-brown. This solution was stirred for 15 min, then PhCH=N(O)Ph (325 mg, 1.65 mmol) in 1 mL of THF was added, and the color quickly lightened to yellow-brown. The solution was stirred for 1.5 h at −78 °C before quenching with 3 mL of a saturated aqueous $NaHCO_3$ solution. The solution was then warmed to room temperature, and an additional 20 mL of this aqueous base was added. The usual CH_2Cl_2 extracting (3 × 20 mL), Na_2SO_4 drying, and solvent removing by rotary evaporation yielded a crude yellow-brown solid that was triturated with ether to remove the unreacted starting iron complex **1** and unreacted nitrone. This left 488.4 mg (68%) of a light yellow-brown solid **9**: mixture of diastereomers; IR (THF, cm^{-1}) 3330 br, 3060, 3035, 1915, 1608, 1488, 1434, 1179, 1028, 822, 752, 701, 609; ^{1}H NMR ($CDCl_3$, major diastereomer) 7.63–6.74 (m, 25 H), 5.91 (s, br, 1 H, exchanges with D_2O), 5.15 (dd, J = 9, 6 Hz, 1 H), 4.34 (d, J = 1 Hz, 5 H), 3.45 (dd, J = 14, 6 Hz, 1 H), 2.73 (dd, J = 14, 9 Hz, 1 H). Anal. Calcd for $C_{39}H_{34}NO_3PFe$: C, 71.89; H, 5.26; N, 2.15. Found: C, 71.81; H, 5.25; N, 2.08.

Reductive Cleavage of the N–O Bond in Complex 9. Hydroxyamine iron complex **9** (50 mg, 0.077 mmol) was dissolved in 5 mL of THF and titanium trichloride (0.24 mL of a 20% aqueous solution, 0.307 mmol) was added at room temperature, and the yellow-brown color immediately lightened slightly. Analysis by TLC at t = 45 min showed no starting material present and a product which cochromatographed with a known mixture of diastereomers of complex **7**/**8** (R = R′ = Ph). The usual

saturated aqueous $NaHCO_3$ (20 mL) addition followed by CH_2Cl_2 extraction (2 × 20 mL) and Na_2SO_4 drying yielded a yellow solution from which the solvent was removed by rotary evaporation and pumping under vacuum to yield 48.5 mg (99%) of a yellow solid whose ^1H NMR was consistent with assignment as a mixture of diastereomers of complex **7/8** (R = R′ = Ph) by comparison with spectra obtained above.

General Experimental for the Condensation with Cyclic Nitrones. The lithium and aluminum enolates of starting acetyl **1** were generated exactly as described above. Fifteen minutes after the diisobutylaluminum chloride addition at −78 °C, the cyclic nitrone **10** (186 mg, 1.65 mmol) dissolved in 2 mL of THF was added slowly. The deep orange-brown of the aluminum enolate quickly lightened to yellow-brown. The solution was allowed to stir for 1 h at −78 °C, then 0.5 mL of saturated aqueous $NaHCO_3$ was added, and the solution was allowed to warm to room temperature. An additional 20 mL of THF was then added followed by titanium trichloride (5 mL of a 20% aqueous solution, 6.6 mmol). The orange-yellow rapidly lightened, and the solution was then allowed to stir at room temperature overnight. An additional 20 mL of saturated aqueous $NaHCO_3$ was added followed by the usual CH_2Cl_2 extracting (3 × 30 mL), Na_2SO_4 drying, and solvent removing by rotary evaporation, yielding a crude orange solid. This product was chromatographed on a silica gel column (1.5 × 15 cm, 60–200 mesh) to yield three bands. The first band, eluted with CH_2Cl_2 (34.9 mg, 7%), was recovered starting material **1**. A second band (77.3 mg, 12%, yellow solid) eluted with EtOH and was presumed to be unreduced hydroxylamine complex, since retreatment in THF with 20% aqueous $TiCl_3$ produced a product identical with the third band which eluted from this column with 50:1 EtOH:Et_3N. This complex **13/14** (468.2 mg, 77%) was an orange solid and the total yield (combined bands 2 and 3) was 89%. **13/14**: mixture of diastereomers; IR (CH_2Cl_2, cm^{-1}) 3079, 3048, 2960, 2868, 1915, 1602, 1480, 1461, 1432, 1379, 1186, 1092, 1029, 1014, 999, 938, 841, 824; ^1H NMR ($CDCl_3$, major diastereomer) 744 (m, 15 H), 4.41 (d, J = 1 Hz, 5 H), 3.15 (m, 1 H), 3.08 (dd, J = 15, 7 Hz, 1 H), 2.78 (dd, J = 15, 5 Hz, 1 H), 1.82 (m, 2 H), 1.47 (t, J = 7 Hz, 2 H), 1.13 (s, 3 H), 1.04 (s, 3 H). Anal. Calcd for $C_{32}H_{34}NO_2PFe$: C, 69.70; H, 6.22; N, 2.54. Found: C, 69.57; H, 6.50; N, 2.61. Complex **15** was synthesized analogously (32%) except the solution was allowed to warm from −78 to −20 °C over 2 h, and the reaction was quenched at −20 °C. Product: mp 139–140 °C dec (CH_2Cl_2/Et_2O); IR (CH_2Cl_2, cm^{-1}) 3079, 3050, 2958, 2869, 1914, 1612, 1479, 1432, 1378, 1364, 1186, 1158, 1091, 999, 975, 873, 845, 826, 686, 609; ^1H NMR (C_6D_6) 7.69 (m, 6 H), 7.04 (m, 9 H), 4.25 (d, J = 1 Hz, 5 H), 3.56 (d, J = 16 Hz, 1 H), 3.10 (d, J = 16 Hz, 1 H), 1.65 (m, 2 H), 1.49 (m, 2 H), 1.13 (s, 3 H), 1.07 (s, 3 H). Anal. Calcd for $C_{33}H_{36}NO_2PFe$: C, 70.09; H, 6.42; N, 2.48. Found: C, 69.84; H, 6.36; N, 2.58. **16**: 71%, quenched at −78 °C; mixture of three diastereomers; IR (CH_2Cl_2, cm^{-1}) 3075, 3039, 2962, 2935, 2878, 1912, 1601, 1491, 1479, 1450, 1431, 1378, 1361, 1310, 1185, 1118, 1092, 1028, 998, 941, 843, 822; ^1H NMR ($CDCl_3$, ratio, 2.5:1.8:1) Cp resonances 4.54, 4.56, and 4.58 (d, J = 1 Hz, 5 H total), Me resonances 1.11 and 0.69, 1.10 and 0.68, 1.16 and 0.63 (s, 6 H total); the other resonances were not easily assignable to a specific diastereomer. Anal. Calcd for $C_{38}H_{38}NO_2PFe$: C, 72.73; H, 6.10; N, 2.23. Found: C, 72.93; H, 6.36; N, 2.34.

Synthesis β-Lactams from β-Amino Iron Acyls. NBS Cleavage of 7 (R = R′ = Ph). Diastereomerically pure iron complex **7** (R = R′ = Ph; 246 mg, 0.387 mmol) was dissolved in 10 mL of CH_2Cl_2 (passed over alumina) and cooled to −42 °C. *N*-Bromosuccinimide (79 mg, 0.445 mmol) was dissolved in 2 mL of CH_2Cl_2 and added slowly to the solution containing the iron complex. The color slowly darkened from orange to green. After 20 min at −42 °C, the solution was allowed to warm to 0 °C and the green darkened; however, after an additional 20 min there was still some starting material present. An additional 79 mg (0.445 mmol) of NBS was then added, and the color immediately deepened. Analysis by TLC after 30 min showed no starting material present, so 30 mL of a 1 N aqueous NaOH solution was added and the aqueous layer was extracted with CH_2Cl_2 (2 × 30 mL). The combined extracts were dried (Na_2SO_4) and the solvent removed by rotary evaporation to leave a crude green product. This crude product was triturated with several small portions of ether, and the solvent was then removed from these combined portions by rotary evaporation. The resulting green residue was applied to a 0.5-mm silica gel prep plate that was developed with CH_2Cl_2. The green η^5-CpFe(PPh_3)(CO)Br band and an unresolved colorless band (R_f 0.5) were scraped together and reapplied to a 0.5-mm silica gel prep plate. Development with 3:2 ether:hexane yielded a white solid (R_f 0.7, 12 mg, 10%) in addition to η^5-CpFe(PPh_3)(CO)Br. The white solid was assumed to be 1-(4-bromophenyl)-4-phenylazetidone: mp 119–120 °C (hexane/ether); IR (CH_2Cl_2, cm^{-1}) 3039, 2975, 2910, 1755, 1601, 1499, 1428, 1380, 1159, 1125, 1080, 1069, 1047, 1015, 987, 839; ^1H NMR ($CDCl_3$) 7.60–7.10 (m, 9 H), 4.98 (dd, J = 5, 3 Hz, 1 H), 3.57 (dd, J = 15, 5 Hz, 1 H), 2.95 (dd, J = 15, 3 Hz, 1 H); mass spectrum, m/e 304 (0.6), 303 (3.6), 302 (0.4), 301 (4), 260 (3.1), 258 (3.0), 199 (5.0), 197 (4.9), 157 (2.5), 155 (2.6), 104 (100), 78 (9.4).

Typical Experimental for I_2 Cleavage To Yield β-Lactams. Iron complex **7** (R = R′ = Ph, 100 mg, 0.16 mmol) was dissolved in 3 mL of CH_2Cl_2 and cooled to −42 °C. *N*,*N*-Dimethylaniline (0.040 mL, 0.32 mmol) was added along with solid I_2 (176 mg, 0.69 mmol). After the solution stirred under N_2 at −42 °C for 6 h, additional I_2 (88 mg, 0.35 mmol) was added and the solution was allowed to slowly warm to 0 °C overnight. The reaction mixture was quenched with aqueous $NaHSO_3$ (10%, 20 mL) and made basic with aqueous NaOH (10%, 10 mL). After the mixture was extracted with CH_2Cl_2 (3 × 20 mL), the CH_2Cl_2 extracts were combined and dried over $MgSO_4$. Removal of solvent on a rotary evaporator left a deep green solid that was chromatographed on a 2-mm silica gel prep plate (4:1:1, hexane:CH_2Cl_2:ethyl acetate) to yield 28 mg (R_f 0.3, 80%) of 1,4-diphenyl-2-azetidinone as a white solid: mp 152–153 °C (MeOH); IR ($CHCl_3$, cm^{-1}) 3028, 2981, 2945, 1749, 1608, 1509, 1467, 1382, 1159, 1095, 986; ^1H NMR ($CDCl_3$) 7.72–7.00 (m, 10 H), 5.01 (dd, J = 5.5, 2.5 Hz, 1 H), 3.56 (dd, J = 15, 5.5 Hz, 1 H), 2.94 (dd, J = 15, 2.5 Hz, 1 H); mass spectrum, m/e (M^+) 223.1 (20.9), 180 (18.5), 104 (100), 77 (19.3). When the same procedure as that described above was used except that 3 equiv of I_2 was used and the reaction was run at room temperature for 90 min, the desired β-lactam was isolated (57%) in addition to 1-(phenylamino)-1-phenyl-2-iodoethane (yellow oil, R_f 0.7, 22 mg, 40%): IR ($CHCl_3$) 3030, 2999, 1609, 1510, 1462, 1325; ^1H NMR ($CDCl_3$) 7.40–6.60 (m, 10 H), 4.45 (m, 1 H), 4.23 (d, v br, J = 3 Hz, 1 H, NH), 3.58 (dd, J = 11, 5 Hz, 1 H), 3.43 (dd, J = 11, 8 Hz, 1 H); mass spectrum, m/e (M^+) 323.0 (14.7), 182 (100), 106 (24.4), 104 (40.7), 77 (21.8).

Typical Bromine Cleavage for β-Lactam Formation. Diastereomerically pure iron complex **7** (R = CH_2Ph, R′ = Ph; 100 mg, 0.154 mmol) was dissolved in 4 mL of carbon disulfide, and this solution was degassed with N_2. The flask was then cooled to −78 °C, and bromine (0.20 mL of a 1.0 M solution in CS_2 (freshly made), 0.20 mmol) was added slowly. The orange of the solution immediately turned deep green. This solution was stirred for 15 min at −78 °C and then 5 mL of saturated aqueous $NaHCO_3$ was added. The solution was then warmed to room temperature and extracted with CH_2Cl_2 (2 × 20 mL). The extracts were dried (Na_2SO_4), and the solvent was removed by rotary evaporation to yield a crude green product that was chromatographed on a 2-mm silica gel prep plate with CH_2Cl_2 to yield η^5-CpFe(PPh_3)(CO)Br (R_f 0.6) and the desired β-lactam 1-benzyl-4-phenylazetidinone (29 mg, 79%) as a light yellow oil (R_f 0.2): IR (CH_2Cl_2, cm^{-1}) 3079, 3042, 2970, 2935, 1740, 1499, 1458, 1393, 1359, 1308, 1200, 1127, 1081, 1046, 1031, 991, 944, 808; ^1H NMR ($CDCl_3$) 7.27 (m, 10 H), 4.81 (d, J = 15 Hz, 1 H), 4.41 (dd, J = 5, 2 Hz, 1 H), 3.77 (d, J = 15 Hz, 1 H), 3.35 (dd, J = 15, 5 Hz, 1 H), 2.88 (dd, J = 15, 2 Hz, 1 H); exact mass calcd for $C_{16}H_{15}NO$ 237.1154, found 237.1157. 1-*n*-Propyl-4-phenylazetidinone (R_f 0.15, CH_2Cl_2, 82%) was synthesized analogously: IR (CH_2Cl_2, cm^{-1}) 3053, 2979, 2945, 2895, 1740, 1462, 1405, 1365, 1208, 1092, 1019; ^1H NMR (C_6D_6) 7.11–6.84 (m, 5 H), 3.93 (dd, J = 5.5, 2.5 Hz, 1 H), 3.13 (m, 1 H), 2.88 (dd, J = 14.5, 5.5 Hz, 1 H), 2.54 (m, 1 H), 2.46 (dd, J = 14.5, 2.5 Hz, 1 H), 1.18 (m, 2 H), 0.62 (t, J = 8 Hz, 3 H); mass spectrum, m/e (M^+) 189 (3.7), 118 (20), 105 (10), 104 (100), 91 (17), 78 (10). 1-*n*-Propyl-4-(2(*Z*)-methyl-1-phenylethylene)azetidinone: light yellow oil, R_f 0.15, CH_2Cl_2, 62%; IR (CH_2Cl_2, cm^{-1}) 3040, 2975, 2942, 2888, 1734, 1492, 1441, 1403, 1328, 1193, 1122, 1025, 1003, 909, 651; ^1H NMR ($CDCl_3$) 7.78–7.22 (m, 5 H), 6.56 (s br, 1 H), 4.17 (dd, J = 5, 2 Hz, 1 H), 3.36 (dt, J = 14, 7 Hz, 1 H), 3.13 (dd, J = 15, 5 Hz, 1 H), 2.90 (dt, J = 14, 7 Hz, 1 H), 2.80 (dd, J = 14, 2 Hz, 1 H), 1.85 (d, J = 1 Hz, 3 H), 1.59 (m, 2 H), 0.93 (t, J = 8 Hz, 3 H); exact mass calcd for $C_{15}H_{19}NO$ 229.1466, found 229.1440. 1-Cyclohexyl-4-phenylazetidinone: light yellow oil, R_f 0.2, CH_2Cl_2, 66%; IR (CH_2Cl_2, cm^{-1}) 3064, 2943, 2875, 1735, 1458, 1396, 1369, 1312, 1204, 1127, 1082, 1055, 1031, 989, 830; ^1H NMR ($CDCl_3$) 7.36 (m, 5 H), 4.58 (dd, J = 5, 2 Hz, 1 H), 3.40 (m, 1 H), 3.29 (dd, J = 15, 5 Hz, 1 H), 2.76 (dd, J = 15, 2 Hz, 1 H), 2.02–0.78 (m, 10 H); exact mass calcd for $C_{15}H_{19}NO$, 229.1466, found 229.1457. 1-*n*-Propyl-4-isopropylazetidinone: light yellow oil, R_f 0.15, CH_2Cl_2, 56%; IR (CH_2Cl_2, cm^{-1}) 1735; ^1H NMR ($CDCl_3$) 3.44 (m, 1 H), 3.39 (m, 1 H), 2.94 (m, 1 H), 2.83 (dd, J = 14, 5 Hz, 1 H), 2.57 (dd, J = 14, 2 Hz, 1 H), 1.93 (m, 1 H), 1.60 (m, 2 H), 0.98 (d, J = 7 Hz, 3 H), 0.92 (t, J = 7 Hz, 3 H), 0.89 (d, J = 7 Hz, 3 H); exact mass calcd for $C_9H_{17}NO$ 155.1332, found 155.1321.

Synthesis of Bicyclic β-Lactams. The bicyclic β-lactam derived from iron acyl **13** was synthesized according to the Br_2 procedure described above except CH_2Cl_2 was used instead of CS_2: light yellow oil, R_f 0.20, CH_2Cl_2, 31%; IR (CH_2Cl_2, cm^{-1}) 2976, 2944, 2881, 1740, 1458, 1374, 1346, 1295, 1225, 1190, 1092, 1023, 819; ^1H NMR ($CDCl_3$) 3.69 (m, 1 H), 3.07 (dd, J = 16, 5 Hz, 1 H), 2.57 (dd, J = 16, 2 Hz, 1 H), 2.06 (m, 1 H), 1.98 (m, 2 H), 1.68 (m, 1 H), 1.54 (s, 3 H), 1.18 (s, 3 H); mass spectrum, m/e 139.12 (M^+). The bicyclic β-lactam derived from iron

acyl **15** was synthesized analogously (cleavage also run in CH_2Cl_2 rather than CS_2: light yellow oil, R_f 0.15, CH_2Cl_2, 59%; IR (CH_2Cl_2, cm^{-1}) 2972, 2939, 2880, 1738, 1461, 1441, 1382, 1314, 1270, 1188, 1124, 1002, 813; ^{1}H NMR ($CDCl_3$) 2.77 (d, J = 15 Hz, 1 H), 2.70 (d, J = 15 Hz, 1 H), 2.07 (m, 2 H), 1.87 (m, 2 H), 1951 (s, 3 H), 1.42 (s, 3 H), 1.24 (s, 3 H); mass spectrum, m/e 153.12 (M^+). The β-lactam derived from iron acyl **16** was synthesized by the following procedure. Iron complex **16** (mixture of diastereomers, (95 mg, 0.144 mmol) was dissolved in 5 mL of CH_2Cl_2 and stirred at room temperature. Iodine (146 mg, 0.575 mmol) was added as a solid; however, the orange color did not rapidly change to green. Triethylamine (0.20 mL, 1.43 mmol) was added, and the solution immediately turned dark green. The solution was stirred for 1 h at room temperature when analysis by TLC showed no starting material present. The reaction was worked up by the addition of 10 mL of 10% aqueous $Na_2S_2O_5$ to reduce the excess iodine, followed by the addition of 30 mL of saturated aqueous $NaHCO_3$. The aqueous layer was extracted with CH_2Cl_2 (3 × 20 mL), the combined extracts were dried (Na_2SO_4), and the solvent was removed by rotary evaporation to yield a crude green product. This crude product was chromatographed by radial chromatography (2-mm silca gel), first with CH_2Cl_2 to elute η^5-CpFe(PPh$_3$)(CO)I, followed by elution with EtOH to yield the desired β-lactam (24.5 mg, 79%) as a light yellow oil: IR (CH_2Cl_2, cm^{-1}) 3000, 2918, 2844, 1725, 1581, 1439, 1370, 1353, 1316, 1212, 1192, 1100; ^{1}H NMR ($CDCl_3$) 7.27 (m, 5 H), 3.90 (m, 1 H), 3.28 (dd, J = 16, 6 Hz, 1 H), 3.20 (dd, J = 13, 8 Hz, 1 H), 2.73 (dd, J = 16, 3 Hz, 1 H), 2.57 (ddd, J = 14, 12, 8 Hz, 1 H), 2.23 (ddd, J = 14, 8, 2 Hz, 1 H), 1.54 (s, 3 H), 0.81 (s, 3 H); exact mass calcd for $C_{14}H_{17}NO$ 215.1310, found 215.1291.

Synthesis of α,β-Unsaturated Iron Acyls. A typical, large-scale experimental procedure for the preparation of α,β-unsaturated iron acyls (*E*)-**19** and (*Z*)-**20** is described in ref 14. The synthesis of the (*E*)-cinnamyl iron acyl **22** was performed analogously to yield the acetylated product (64%, mixture of diastereomers): IR (CH_2Cl_2, cm^{-1}) 3038, 2990, 1910, 1728, 1601, 1482, 1438, 1372, 1232, 1169, 1105, 1092, 1068, 1029, 1002, 925, 829; ^{1}H NMR (C_6D_6, 360 MHz) 7.69 (m, 6 H), 7.56–6.97 (m, 14 H), 6.50 and 6.36 (dd, J = 4.3, 3.8, 5.4, 1.8 Hz, 1 H total), 4.38 and 4.08 (d, J = 1 Hz for both, 5 H total), 4.07 and 3.73 (dd, J = 18.5, 5.4, 17.9, 3.8 Hz, 1 H total), 3.45 and 3.02 (dd, J = 17.9, 4.3, 18.5, 1.8 Hz, 1 H total), 1.67 and 1.56 (s, 3 H total). Anal. Calcd for $C_{33}H_{31}O_4PFe$: C, 69.77; H, 5.19. Found: C, 69.71; H, 5.02.

Using the KO-*t*-Bu elimination procedure described in ref 14, enone **22**, with data reported earlier above, was prepared in 75% yield. Similar procedures were used to prepare the α,β-unsaturated iron acyls **23**–**25** which showed the following data. **23**: IR (CH_2Cl_2, cm^{-1}) 1915, 1630, 1560, 1430; ^{1}H NMR ($CDCl_3$) 7.5–7.3 (m, 15 H), 6.42 (d, J = 15 Hz, 1 H), 5.41 (dd, J = 15, 7 Hz, 1 H), 4.38 (d, J = 1 Hz, 5 H), 2.16 (m, 1 H), 0.94 (d, J = 7 Hz, 6 H). Anal. Calcd for $C_{30}H_{29}FeO_2P$: C, 70.88; H, 5.75. Found: C, 70.92; H, 6.06. **24**: mp 130–131.5 °C; IR (CH_2Cl_2, cm^{-1}) 1920, 1625, 1580, 1440; ^{1}H NMR ($CDCl_3$) 7.6–7.3 (m, 15 H), 6.57 (br s, 1 H), 4.40 (d, J = 1 Hz, 5 H), 1.55 (br s, 3 H), 1.39 (br s, 3 H). Anal. Calcd for $C_{29}H_{27}FeO_2P$: C, 70.48; H, 5.51. Found: C, 70.51; H, 5.73. **25**: IR (CH_2Cl_2, cm^{-1}) 1915, 1600, 1560, 1435; ^{1}H NMR ($CDCl_3$) 7.6–7.3 (m, 15 H), 6.47 (d, J = 17 Hz, 1 H), 5.97–5.82 (m, 3 H), 4.45 (d, J = 1 Hz, 5 H), 2.10 (m, 2 H), 1.42 (sextet, J = 7 Hz, 2 H), 0.90 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{32}H_{31}FeO_2P$: C, 71.93; H, 5.85. Found: C, 72.01; H, 5.87.

CpFe(CO)(PPh$_3$)(C(O)CH$_2$CH=CH$_2$) (21). Potassium *tert*-butoxide (234 mg, 2.08 mmol) was dissolved in 4 mL of THF and cooled to 0 °C. Iron complex **19** (100 mg, 0.208 mmol) was dissolved in 2 mL of THF and added to this solution. The color of the solution went from orange to deep red-brown quickly. Analysis at t = 1 h by TLC showed approximately a 1:1 mixture of starting material and product. Analysis at t = 3 h showed no change. The reaction was then worked up by the addition of 30 mL of saturated aqueous $NaHCO_3$, followed by CH_2Cl_2 extraction (2 × 30 mL), Na_2SO_4 drying, and removal of solvent, first by rotary evaporation and then by pumping under vacuum, yielding 89.9 mg (90%) of a orange solid which was by ^{1}H NMR a 1.07:1 mixture of starting material **19** to product **21**. **(a) Reaction of *Z* Enone 20 with *n*-PrNHLi.** Propylamine (distilled off KOH, 0.035 mL, 0.42 mmol) and *n*-BuLi (0.26 mL of a 1.6 M solution in hexanes, 0.42 mmol) were stirred together in 4 mL of THF at −78 °C for 1 h. Iron complex **20** (88.3 mg, 0.184 mmol) in 2 mL of THF was then added dropwise to the base, and the color of the solution immediately changed from orange to a deep red-brown. This solution was stirred for 1.5 h at −78 °C and then was quenched by the addition of 20 mL of saturated aqueous $NaHCO_3$. A workup analogous to the procedure above yielded 87.1 mg (98%) of an orange solid **21**: mp 147–149 °C (CH_2Cl_2/Et_2O); IR (CH_2Cl_2, cm^{-1}) 3095, 3065, 2986, 2935, 1921, 1644, 1608, 1490, 1441, 1194, 1100, 1003, 971, 924, 881, 831, 619, 579, 538; ^{1}H NMR (C_6D_6) 7.69 (m, 6 H), 7.06 (m, 9 H), 6.05 (m, 1 H), 5.00 (dd, J = 11, 1 Hz, 1 H), 4.97 (dd, J = 16, 1 Hz, 1 H), 4.26 (d, J = 1 Hz, 5 H), 3.83 (ddd, J = 15, 7.5, 1 Hz, 1 H), 3.57 (ddd, J = 15, 7, 1 Hz, 1 H). Anal. Calcd for $C_{28}H_{25}O_2PFe$: C, 70.01; H, 5.25. Found: C, 70.23; H, 5.41. **(b) Reaction of *E* Enone 19 with LDA–HMPA.** *n*-Butyllithium (0.195 mL of a 1.6 M solution in hexanes, 0.31 mmol) and diisopropylamine (0.044 mL, 0.31 mmol) were added to 4 mL of THF at 0 °C and stirred for 30 min. After cooling to −78 °C, hexamethylphosphoric triamide (HMPA, 0.163 mL, 0.93 mmol) was added. The HMPA initially separates out as a white solid but slowly goes into solution with stirring. The solution was stirred for 30 min after HMPA addition, and then iron complex **19** (100 mg, 0.208 mmol) in 2 mL of THF was added slowly. The color goes from orange to almost black fairly rapidly. This solution was stirred for 1.5 h at −78 °C and then was quenched at −78 °C by the addition of 3 mL of saturated aqueous $NaHCO_3$. An additional 20 mL of this aqueous base was then added after the solution warmed to room temperature and the workup procedure outlined in (a) above was performed. The crude product was chromatographed on a 1 × 10 cm gravity silica gel column, first eluted with pentane to remove HMPA, followed by elution with ether to yield an orange solid (83.1 mg, 83%) which from ^{1}H NMR was a 4:1 mixture of iron complex **21** and starting material **19**.

General Procedure for the Reaction of Trans α,β-Unsaturated Iron Acyls with Alkyllithiums. *n*-Butyllithium (0.293 mL of a 1.6 M solution in hexanes, 0.47 mmol) was added to 4 mL of THF at −78 °C. Iron complex **19** (155 mg, 0.32 mmol) in 3 mL of THF was added dropwise to the BuLi solution, and the color rapidly changed from orange to deep red. Analysis by TLC at t = 30 min showed no starting material, so the reaction was quenched by the addition of 3 mL of saturated aqueous $NaHCO_3$ at −78 °C. The solution was then warmed to room temperature and an additional 20 mL of this aqueous base was added. The aqueous layer was subjected to the usual CH_2Cl_2 extraction (2 × 30 mL), Na_2SO_4 drying, solvent removal by rotary evaporation, and pumping under vacuum to yield iron complex **26** (R = Me, Nu = *n*-Bu) as an orange solid: 169.3 mg, 97%; mp 118–119 °C (CH_2Cl_2/Et_2O); IR (CH_2Cl_2, cm^{-1}) 3095, 3079, 3059, 2970, 2939, 2880, 1916, 1612, 1488, 1462, 1439, 1382, 1193, 1099, 1032, 1020, 1004, 975, 912, 850, 829, 613, 576, 535, 511; ^{1}H NMR (C_6D_6) 7.72 (m, 6 H), 7.08 (m, 9 H), 4.29 (d, J = 1 Hz, 5 H), 6.19 (dd, J = 18, 5.5 Hz, 1 H), 2.79 (dd, J = 18, 7.5 Hz, 1 H), 2.06 (m, 1 H), 1.41 (m, 1 H), 1.29 (m, 4 H), 1.11 (m, 1 H), 0.90 (t, J = 6 Hz, 3 H), 0.71 (d, J = 6.5 Hz, 3 H). Anal. Calcd for $C_{32}H_{35}O_2PFe$: C, 71.38; H, 6.55. Found: C, 71.28; H, 6.64. Iron complex **26** (R = Me, Nu = Ph; 98%) was synthesized analogously: mp 128–130 °C (ether/petroleum ether); IR (CH_2Cl_2, cm^{-1}) 3096, 3070, 3042, 2978, 2939, 2882, 1917, 1612, 1501, 1488, 1458, 1439, 1318, 1193, 1098, 1033, 1021, 1003, 972, 959, 879, 850, 830, 615, 577, 535, 512; ^{1}H NMR (C_6D_6) 7.75 (m, 6 H), 7.32–6.94 (m, 14 H), 4.06 (d, J = 1 Hz, 5 H), 3.67 (dd, J = 17, 7 Hz, 1 H), 3.39 (dq, J = 7, 7 Hz, 1 H), 3.06 (dd, J = 17, 7 Hz, 1 H), 0.97 (d, J = 7 Hz, 3 H). Anal. Calcd for $C_{34}H_{31}O_2PFe$: C, 73.13; H, 5.60. Found: C, 73.29; H, 5.76. Iron complex **26** (R = Ph, Nu = Me; 98%) was also synthesized as above except a MeLi–LiBr complex was used: mp 142–143 °C (ether); IR (CH_2Cl_2, cm^{-1}) 3082, 3052, 3035, 2964, 2936, 2879, 1911, 1610, 1495, 1482, 1451, 1435, 1374, 1188, 1095, 1029, 1017, 1001, 946, 878, 847, 826; ^{1}H NMR 7.69 (m, 6 H), 7.20–6.92 (m, 14 H), 4.24 (d, J = 1 Hz, 5 H), 3.43 (dd, J = 16.9, 9.2 Hz, 1 H), 3.30 (ddq, J = 9.2, 6.5, 3.9 Hz, 1 H), 3.14 (dd, J = 16.9, 3.9 Hz, 1 H), 1.29 (d, J = 6.5 Hz, 3 H). Anal. Calcd for $C_{34}H_{31}O_2PFe$: C, 73.13; H, 5.60. Found: C, 73.44; H, 5.65.

Typical Procedure for the Addition of a Primary Amine Anion to an α,β-Unsaturated Iron Acyl Complex Followed by Protonation. Allylamine (0.031 mL, 0.42 mmol) was added to 4 mL of THF at 0 °C followed by *n*-BuLi (0.26 mL of a 1.6 M solution in hexanes, 0.42 mmol). This solution was stirred at 0 °C for 30 min and then cooled to −78 °C. Iron complex **19** (100 mg, 0.208 mmol) in 2 mL of THF was then added slowly. The color of the solution went from orange to deep red-orange over the course of 15–30 min. The solution was stirred for 1.5 h at −78 °C and then was quenched at that temperature by the addition of 3 mL of saturated aqueous $NaHCO_3$. The solution was warmed to room temperature and an additional 20 mL of this aqueous base was added. The usual CH_2Cl_2 extraction (2 × 30 mL) followed by Na_2SO_4 drying and solvent removal by rotary evaporation yielded a crude product which was chromatographed on a quick gravity silica gel column (1 × 10 cm) with CH_2Cl_2 to remove traces of excess amine in addition to traces of starting complex or *n*-BuLi addition product, followed by elution with EtOH:Et_3N (50:1) to yield complex **26** (R = Me, Nu = NHCH$_2$CH=CH$_2$) as an orange solid (111.1 mg, 99%): mp 135–137 °C (CH_2Cl_2/Et_2O); IR (CH_2Cl_2, cm^{-1}) 3079, 3050, 2968, 2930, 2876, 1913, 1645, 1606, 1483, 1466, 1435, 1374, 1338, 1186, 1148, 1092, 1000, 922, 845, 826; ^{1}H NMR (C_6D_6) 7.65 (m, 6 H), 7.02 (m, 9 H), 5.96 (m, 1 H), 5.20 (ddd, J = 17.5, 2.5, 1 Hz, 1 H), 4.99 (dd, J = 10, 2.5 Hz, 1 H), 4.27 (d, J = 1 Hz, 5 H), 3.35 (dd, J = 17, 8 Hz, 1 H), 3.22 (ddd, J = 14, 5, 2 Hz, 1 H), 3.08 (ddd, J = 14, 6, 1 Hz, 1 H), 2.99 (dd, J = 17, 4 Hz, 1 H),

2.92 (m, 1 H), 0.84 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{31}H_{32}NO_2PFe$: C, 69.28; H, 6.00; N, 2.61. Found: C, 69.09; H, 6.17; N, 2.44. All other amine complexes described below were synthesized analogously, except the reaction with the aniline anion which was allowed to warm from −78 to −42 °C to complete the reaction. **26**, R = Me, Nu = $NHCH_2Ph$, 99%: mp 105–107 °C (none); IR (CH_2Cl_2, cm^{-1}) 3098, 3059, 2992, 2942, 2890, 2861, 1921, 1610, 1490, 1441, 1199, 1125, 1101, 1036, 1005, 831, 548; ^1H NMR (C_6D_6) 7.65 (m, 6 H), 7.42 (d, J = 7 Hz, 2 H), 7.22–6.97 (m, 12 H), 4.21 (d, J = 1 Hz, 5 H), 3.73 (d, J = 13 Hz, 1 H), 3.60 (d, J = 13 Hz, 1 H), 3.36 (dd, J = 18, 8 Hz, 1 H), 3.00 (dd, J = 18, 4.5 Hz, 1 H), 2.94 (m, 1 H), 0.88 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{35}H_{34}NO_2PFe$: C, 71.55; H, 5.83; N, 2.38. Found: C, 71.71; H, 6.05; N, 2.49. **26**, R = Ph, Nu = $NHCH_2CH{=}CH_2$, 79%: mp 122–124 °C (petroleum ether/ether); IR (CH_2Cl_2, cm^{-1}) 3081, 3054, 2978, 2928, 1918, 1645, 1601, 1483, 1452, 1434, 1391, 1350, 1308, 1186, 1118, 1092, 1027, 998, 929, 843, 826; ^1H NMR (C_6D_6) 7.70 (m, 6 H), 7.43 (d, J = 7 Hz, 2 H), 7.25–7.05 (m, 3 H), 7.05 (m, 9 H), 5.92 (m, 1 H), 5.17 (ddd, J = 16, 2, 1 Hz, 1 H), 4.97 (dd, J = 10, 2 Hz, 1 H), 4.20 (d, J = 1 Hz, 5 H), 3.91 (dd, J = 10, 2 Hz, 1 H), 3.57 (dd, J = 17, 10 Hz, 1 H), 3.29 (dd, J = 17, 2 Hz, 1 H), 3.13 (dddd, J = 14.5, 5.5, 2, 1 Hz, 1 H), 3.00 (ddd, J = 14.5, 8 2 Hz, 1 H). Anal. Calcd for $C_{36}H_{34}NO_2PFe$: C, 72.12; H, 5.72; N, 2.34. Found: C, 71.97; H, 5.71; N, 2.34. **26**, R = Ph, Nu = $NHCH_2CH_2OMe$, 63%: mp 108–111 °C; IR (CH_2Cl_2, cm^{-1}) 3090, 3059, 2942, 2908, 2841, 1921, 1605, 1521, 1490, 1459, 1441, 1399, 1311, 1199, 1123, 1100, 1007, 938, 832, 618, 578, 537, 512; ^1H NMR (C_6D_6) 7.66 (m, 6 H), 7.43 (d, J = 7 Hz, 2 H), 7.28–7.02 (m, 12 H), 4.23 (d, J = 1 Hz, 5 H), 3.90 (dd, J = 9, 2 Hz, 1 H), 3.64 (dd, J = 16, 9 Hz, 1 H), 3.34 (m, 1 H), 3.24 (m, 1 H), 3.19 (dd, J = 16, 2 Hz, 1 H), 3.08 (s, 3 H), 2.69 (m, 1 H), 2.53 (m, 1 H). Anal. Calcd for $C_{36}H_{36}NO_3PFe$: C, 70.02; H, 5.88; N, 2.27. Found: C, 70.19; H, 6.01; N, 2.39. **26**, R = Me, Nu = $NHCH_2CH_2OMe$, 69%: mp 149–151 °C dec (ethanol/ether); IR (CH_2Cl_2, cm^{-1}) 3081, 3043, 2962, 2930, 2896, 2835, 1915, 1605, 1481, 1460, 1432, 1372, 1338, 1191, 1119, 1091, 1013, 1000, 975, 941, 842, 822, 608, 570, 529, 506; ^1H NMR (C_6D_6) 7.68 (m, 6 H), 7.03 (m, 9 H), 4.27 (d, J = 1 Hz, 5 H), 3.44–3.28 (m, 3 H), 3.09 (s, 3 H), 2.97 (m, 1 H), 2.93 (dd, J = 18, 4 Hz, 1 H), 2.71 (m, 2 H), 0.83 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{31}H_{34}NO_3PFe$: C, 67.03; H, 6.17; N, 2.52. Found: C, 66.91; H, 6.28; N, 2.45. **26**, R = Me, Nu = NH-*n*-Pr, 97%: mp 133.5–135 °C (Et_2O/CH_2Cl_2); IR (CH_2Cl_2, cm^{-1}) 3095, 3059, 2980, 2944, 2888, 1920, 1612, 1491, 1441, 1342, 1102, 1008, 983, 930, 852, 833, 618, 579, 538, 515; ^1H NMR (C_6D_6) 7.70 (m, 6 H), 7.02 (m, 9 H), 4.28 (d, J = 1 Hz, 5 H), 3.35 (dd, J = 18, 8 Hz, 1 H), 3.02 (dd, J = 18, 5 Hz, 1 H), 2.90 (m, 1 H), 2.52 (m, 1 H), 2.40 (m, 1 H), 1.41 (m, 2 H), 0.89 (d, J = 7 Hz, 3 H), 0.88 (t, J = 7 Hz, 3 H). Anal. Calcd for $C_{31}H_{34}NO_2PFe$: C, 69.02; H, 6.35; N, 2.60. Found: C, 69.06; H, 6.53; N, 2.41. **26**, R = Me, Nu = NHPh, 69%: mp 139.5–141 °C (benzene/ether); IR (CH_2Cl_2, cm^{-1}) 3052, 2968, 2935, 1915, 1602, 1505, 1482, 1433, 1375, 1319, 1243, 1170, 1151, 1092, 998, 972, 933, 842, 826; ^1H NMR (C_6D_6) 7.65 (m, 6 H), 7.20–7.00 (m, 12 H), 6.72 (t, J = 6 Hz, 1 H), 6.50 (d, J = 6 Hz, 1 H), 4.20 (d, J = 1 Hz, 5 H), 3.77 (m, 1 H), 3.44 (dd, J = 18, 3 Hz, 1 H), 2.97 (dd, J = 18, 7 Hz, 1 H), 0.88 (d, J = 7 Hz, 3 H). Anal. Calcd for $C_{34}H_{32}NO_2PFe$: C, 71.21; H, 5.63; N, 2.44. Found: C, 70.90; H, 5.78; N, 2.39. **26**, R = Me, Nu = $N(i\text{-}Pr)_2$, 47%: mp 125–127 °C (CH_2Cl_2/Et_2O); IR (CH_2Cl_2, cm^{-1}) 3090, 2978, 2940, 2882, 1912, 1608, 1488, 1440, 1391, 1364, 1186, 1122, 1098, 1004, 942, 848, 828; ^1H NMR (C_6D_6) 7.72 (m, 6 H), 7.04 (m, 9 H), 4.32 (d, J = 1 Hz, 5 H), 3.59 (ddq, J = 9, 6.6, 2.5 Hz, 1 H), 3.47 (dd, J = 17, 2.5 Hz, 1 H), 3.09 (dd, J = 17, 9 Hz, 1 H), 3.03 (septet, J = 6.8 Hz, 2 H), 1.11 (d, J = 6.8 Hz, 6 H), 0.99 (d, J = 6.8 Hz, 6 H), 0.77 (d, J = 6.6 Hz, 3 H). Anal. Calcd for $C_{34}H_{40}NO_2PFe$: C, 70.22; H, 6.93; N, 2.41. Found: C, 70.18; H, 6.92; N, 2.11.

Typical Experimental Procedure for the Conjugate Addition/Alkylation Sequence for Primary Amine Anions. Benzylamine anion was generated from benzylamine (distilled off KOH, 0.045 mL, 0.42 mmol) and *n*-BuLi (0.26 mL of a 1.6 M solution in hexanes, 0.42 mmol) in 4 mL of THF at 0 °C for 15 min. The solution was then cooled to −78 °C, and iron complex **19** (100 mg, 0.208 mmol) in 2 mL of THF was added slowly. The solution turns from orange to deep red over the course of about 15 min. The solution was stirred for 1.25 h at −78 °C, and then iodomethane (0.040 mL in 0.4 mL of THF, 0.64 mmol) was added dropwise. The deep red immediately went back to light yellow. The solution was allowed to stir for an additional 1.25 h at −78 °C and then the reaction was quenched by the addition of 3 mL of a saturated aqueous $NaHCO_3$ solution. The solution was allowed to warm to room temperature, and an additional 20 mL of this aqueous base was added. The usual CH_2Cl_2 extraction (2 × 30 mL) followed by drying (Na_2SO_4) and removal of solvent by rotary evaporation yielded a crude orange product. This product was chromatographed on a quick gravity silica gel (60–200-mesh, 1 × 10 cm) column and eluted with CH_2Cl_2 to remove excess benzylamine followed by elution with 2% Et_3N in EtOH to yield the desired complex **27** (R = Me, Nu = $NHCH_2Ph$, 116 mg, 95%) as an orange solid: mp 139–140 °C dec (benzene/ether); IR (CH_2Cl_2, cm^{-1}) 3038, 2972, 2938, 2876, 1913, 1592, 1471, 1456, 1433, 1374, 1158, 1092, 1029, 1000, 916, 845, 828; ^1H NMR (C_6D_6) 7.65 (m, 6 H), 7.42–7.10 (m, 5 H), 7.02 (m, 9 H), 4.28 (d, J = 1 Hz, 5 H), 3.78 (d, J = 13 Hz, 1 H), 3.51 (d, J = 13 Hz, 1 H), 2.97 (dq, J = 7, 2 Hz, 1 H), 2.23 (dq, J = 6, 2 Hz, 1 H), 1.41 (d, J = 7 Hz, 3 H), 0.81 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{36}H_{36}NO_2PFe$: C, 71.88; H, 6.03; N, 2.33. Found: C, 72.02; H, 6.28; N, 2.67. Ethyl iodide was added as above; however, the solution was allowed to warm to 0 °C over 3 h to ensure complete alkylation. This yielded complex **27** (R = Et, Nu = $NHCH_2Ph$; 99%): mp 132–133 °C (benzene); IR (CH_2Cl_2, cm^{-1}) 3055, 3036, 2968, 2938, 2879, 1912, 1595, 1481, 1465, 1458, 1436, 1377, 1092, 1029, 999, 929, 842, 828; ^1H NMR (C_6D_6) 7.68 (m, 6 H), 7.38 (d, J = 6 Hz, 2 H), 7.22–6.98 (m, 12 H), 4.28 (d, J = 1 Hz, 5 H), 3.74 (d, J = 15 Hz, 1 H), 3.46 (d, J = 15 Hz, 1 H), 3.00 (m, 1 H), 2.36 (m, 1 H), 2.08 (m, 1 H), 1.26 (t, J = 8 Hz, 3 H), 0.87 (d, J = 7 Hz, 3 H). Anal. Calcd for $C_{37}H_{38}NO_2PFe$: C, 72.20; H, 6.22; N, 2.28. Found: C, 72.30; H, 6.33; N, 2.29. Allyl bromide was also allowed to warm to 0 °C over 3 h and yielded complex **27** (R = $CH_2CH{=}CH_2$, Nu = $NHCH_2Ph$; 92%): mp 135–136 °C (benzene/ether); IR (CH_2Cl_2, cm^{-1}) 3078, 3057, 2968, 2938, 1912, 1635, 1595, 1481, 1454, 1433, 1372, 1148, 1091, 1028, 999, 913, 843, 827; ^1H NMR (C_6D_6) 7.65 (m, 6 H), 7.40–7.08 (m, 5 H), 7.02 (m, 9 H), 6.25 (m, 1 H), 5.26 (dd, J = 17, 2 Hz, 1 H), 5.06 (dd, J = 9, 2 Hz, 1 H), 4.29 (d, J = 1 Hz, 5 H), 3.71 (d, J = 14 Hz, 1 H), 3.41 (d, J = 14 Hz, 1 H), 3.21 (ddd, J = 8.5, 5, 2 Hz, 1 H), 2.88 (ddd, J = 15, 6.5, 5 Hz, 1 H), 2.76 (ddd, J = 15, 8.5, 6.5 Hz, 1 H), 2.47 (dq, J = 6, 2 Hz, 1 H), 0.91 (d, J = 6 Hz, 3 H). Anal. Calcd for $C_{38}H_{38}NO_2PFe$: C, 72.73; H, 6.10; N, 2.23. Found: C, 72.49; H, 6.05; N, 2.25. The benzyl bromide alkylation product **27** (R = CH_2Ph, Nu = $NHCH_2Ph$; 99%) was also synthesized analogously and reacted within an hour at −78 °C: mp 136–137 °C dec (benzene/ether); IR (CH_2Cl_2, cm^{-1}) 3088, 3064, 3038, 2968, 2936, 1921, 1602, 1548, 1496, 1482, 1453, 1435, 1416, 1398, 1381, 1324, 1186, 1093, 1028, 1000, 972, 913, 848, 831; ^1H NMR (C_6D_6) 7.70 (m, 6 H), 7.58 (d, J = 7 Hz, 2 H), 7.38 (d, J = 7 Hz, 2 H), 7.30–6.90 (m, 15 H), 3.99 (d, J = 1 Hz, 5 H), 3.63 (dd, J = 8, 6 Hz, 1 H), 3.58 (d, J = 14 Hz, 1 H), 3.46 (dd, J = 14, 8 Hz, 1 H), 3.31 (d, J = 1j Hz, 1 H), 2.95 (dd, J = 14, 6 Hz, 1 H), 2.66 (q br, J = 7 Hz, 1 H), 0.90 (d, J = 7 Hz, 3 H). Anal. Calcd for $C_{42}H_{40}NO_2PFe$: C, 74.44; H, 5.95; N, 2.07. Found: C, 74.74; H, 6.04; N, 2.35. Carbon methylated complex **27** (R = Me, Nu = NH-*n*-Pr; 53%) was also synthesized as above: mp 130–132 °C (CH_2Cl_2, Et_2O); IR (CH_2Cl_2, cm^{-1}) 3055, 2978, 2942, 2881, 1917, 1599, 1487, 1439, 1379, 1099, 1005, 917, 891, 850, 831, 570, 535, 511; ^1H NMR (C_6D_6) 7.65 (m, 6 H), 7.05 (m, 9 H), 4.28 (d, J = 1 Hz, 5 H), 3.04 (dq. J = 8, 1 Hz, 1 H), 2.53 (m, 1 H), 2.25 (m, 2 H), 1.52 (m, 1 H), 1.41 (d, J = 8 Hz, 3 H, with underlying multiplet 1 H), 0.90 (t, J = 8 Hz, 3 H), 0.86 (d, J = 8 Hz, 3 H). Anal. Calcd for $C_{32}H_{36}NO_2PFe$: C, 69.44; H, 6.56; N, 2.53. Found: C, 69.70; H, 6.72; N, 2.56.

Typical Experimental Procedure for Conjugate Addition/Alkylation with Alkyllithium (Aryllithium)/Alkyl Halide. Phenyllithium (1.16 mL of a 1.8 M solution in 70/30 cyclohexane/ether, 2.08 mmol) was added to 10 mL of THF at −78 °C. Iron complex **19** (500 mg, 1.04 mmol) in 4 mL of THF was added slowly. The solution turned from orange to deep red fairly rapidly. The solution was stirred for 1 h at −78 °C, then iodomethane (0.19 mL in 0.6 mL of THF, 3.0 mmol) was added slowly, and the color immediately began to lighten back to yellow-orange. This solution was stirred for 1 h at −78 °C and then was quenched by the addition of 3 mL of a saturated aqueous $NaHCO_3$ solution. The solution was then warmed to room temperature, and an additional 20 mL of this base solution was added. The aqueous solution was extracted with CH_2Cl_2 (3 × 30 mL), the organic extracts were then dried over Na_2SO_4, and the solvent was removed by rotary evaporation. The crude orange product was chromatographed on a quick silica gel column (1 × 18 cm, 60–200 mesh) eluted with 10:1 CH_2Cl_2:Et_2O to yield the desired product **27** (R = Me, Nu = Ph) as an orange solid (595 mg, 99%): mp 161–162 °C dec (CH_2Cl_2/Et_2O); IR (CH_2Cl_2, cm^{-1}) 3088, 3062, 3036, 2972, 2938, 2879, 1911, 1602, 1495, 1482, 1451, 1434, 1365, 1092, 1000, 888, 845, 828, 687; ^1H NMR (C_6D_6) 7.75 (m, 6 H), 7.22–6.94 (m, 14 H), 4.29 (d, J = 1 Hz, 5 H), 3.26 (dq, J = 8.5, 7.5 Hz, 1 H), 3.02 (dq, J = 8.5, 7.5 Hz, 1 H), 1.16 (d, J = 7.5 Hz, 3 H), 0.63 (d, J = 7.5 Hz, 3 H). Anal. Calcd for $C_{35}H_{33}O_2PFe$: C, 73.43; H, 5.81. Found: C, 73.30; H, 5.75. A MeLi–LiBr complex was added analogously to the cinnamyl iron complex **22** (94%); however, the enolate formed by the initial conjugate addition qualitatively reacts much more slowly with MeI than the enolate generated above. The reaction product is shown in eq 12 (mixture of diastereomers): IR (CH_2Cl_2, cm^{-1}) 3055, 3036, 2968, 2938, 2879, 1911, 1605, 1492, 1481, 1449, 1433, 1368, 1186, 1092, 1028, 1000, 890, 845, 828, 686, 668; ^1H NMR (C_6D_6) 7.85–7.00 (m, 20 H), 4.30 and 4.25

(d, J = 1 Hz, 5 H total), 3.53 and 3.47 (dq, J = 7.5, 7.1, 8.5, 6.8 Hz, 1 H total), 3.32 and 3.14 (dq, J = 7.5, 7.1, 8.5, 6.8 Hz, 1 H total), 1.42 and 1.01 (d, J = 6.8, 7.5 Hz, 3 H total), 0.89 and 0.51 (d, J = 7.5, 6.8 Hz, 3 H total). Anal. Calcd for $C_{35}H_{33}O_2PFe$: C, 73.43; H, 5.81. Found: C, 73.16; H, 6.17.

In an analogous fashion PhLi was added to the cinnamyl iron complex **22** followed by reaction with MeI to give the product shown in eq 15 in 85% yield (11:1 ratio of diastereomers). Major product: IR (CH_2Cl_2, cm^{-1}) 1910, 1600; ^1H NMR ($CDCl_3$) 7.70-6.80 (m, 25 H), 4.35 (d, J = 1 Hz, 5 H), 4.07 (d, J = 5 Hz, 1 H), 3.56 (dq, J = 5, 7.5 Hz, 1 H), 0.89 (t, J = 7.5 Hz, 3 H). Anal. Calcd for $C_{40}H_{35}FeO_2P$: C, 75.71; H, 5.56. Found: C, 75.51; H, 5.87.

Oxidative Cleavage Reaction To Yield Erythro Ester 28 and Hydrolysis To Yield Erythro Acid 29. Diastereomerically pure iron complex **27** (R = Me, Nu = Ph, 100 mg, 0.175 mmol) was dissolved in 4 mL of CS_2:EtOH (degassed with N_2), with enough CH_2Cl_2 added to maintain solubility of this complex at -78 °C. Bromine (0.21 mL of a freshly made 1.0 M solution in CS_2, 0.21 mmol) was added slowly at -78 °C. The solution instantly turned from orange to deep green upon bromine addition. The solution was stirred for 10 min, and analysis by TLC showed no starting material present. A 5% NH_4Cl solution (20 mL) was then added, and this aqueous solution was extracted with CH_2Cl_2 (2 × 30 mL). These CH_2Cl_2 extracts were dried (Na_2SO_4), and the solvent was removed by rotary evaporation to yield a crude green product. This product was chromatographed on a 2-mm silica gel prep plate with 4:1 pentane:ethyl acetate to yield a light yellow oil (R_f 0.8, 32.9 mg, 83%). **28**: IR (CH_2Cl_2, cm^{-1}) 3098, 3070, 3039, 2981, 2941, 2884, 1726, 1608, 1498, 1455, 1380, 1341, 1305, 1229, 1180, 1149, 1099, 1075, 1028, 969, 915, 865, 850; ^1H NMR ($CDCl_3$) 7.35-7.15 (m, 5 H), 4.20 (dq, J = 7, 3.5 Hz, 2 H), 2.89 (dq, J = 10, 7 Hz, 1 H), 2.58 (dq, J = 10, 6 Hz, 1 H), 1.29 (t, J = 7 Hz, 3 H), 1.25 (d, J = 7 Hz, 3 H), 0.93 (d, J = 6 Hz, 3 H). This ester (20 mg, 0.097 mmol) was placed into 20 mL of 95:5 ethanol:water, and sodium hydroxide (300 mg, 7.5 mmol) was added. The solution was refluxed for 1.5 h, and then the ethanol was removed by rotary evaporation. This solution was acidified with concentrated HCl and extracted with ether (3 × 20 mL). The ether extracts were dried over $MgSO_4$, and the ether was removed by rotary evaporation and pumping under vacuum to yield 6.0 mg (35%) of a yellow-white solid **29**: mp 132-134 °C (hexane/ether);[54] IR (CH_2Cl_2, cm^{-1}) 3500, 3400-2500 underlying OH, 3096, 3039, 2965, 2939, 2881, 1709, 1604, 1497, 1458, 1381, 1298, 1218, 1156, 1125, 1080, 881, 832; ^1H NMR ($CDCl_3$) 12.8 (s, v br, 1 H), 7.34-7.15 (m, 5 H), 2.91 (dq, J = 10, 7 Hz, 1 H), 2.61 (dq, J = 10, 7 Hz, 1 H), 1.32 (d, J = 7 Hz, 3 H), 0.97 (d, J = 7 Hz, 3 H).

General Procedure for Cis Disubstituted β-Lactam Formation. Iron complex **27** (R = Me, Nu = $NHCH_2Ph$, 104 mg, 0.173 mmol) was dissolved in 3 mL of CS_2 with a minimum amount of CH_2Cl_2 added to maintain the solubility of the complex at -78 °C, and the solution was degassed at room temperature with N_2. (In some cases, improved yields of β-lactams were noted when 2 equiv of anhydrous K_2CO_3 was also added to the solution.) .Bromine (0.208 mL of a freshly made 1.0 M solution in CS_2, 0.208 mmol) was added dropwise, and the solution rapidly turned from orange to deep green. The solution was stirred for 15 min at -78 °C and then 20 mL of water was added. The usual CH_2Cl_2 extracting (2 × 30 mL), Na_2SO_4 drying, and removing of solvent by rotary evaporation yielded a crude green product which was chromatographed on a 2-mm silica gel prep plate (10:1, CH_2Cl_2:Et_2O) to yield the desired β-lactam **30** as a light yellow oil (R_f 0.25, 25.6 mg, 78%). β-Lactam **30**:[51] IR (CH_2Cl_2, cm^{-1}) 3098, 3042, 2981, 2938, 2905, 1741, 1501, 1456, 1438, 1409, 1386, 1359, 1239, 1201, 1156, 1143, 1113, 1080, 1031, 969, 912; ^1H NMR ($CDCl_3$) 7.38-7.22 (m, 5 H), 4.60 (d, J = 16 Hz, 1 H), 4.10 (d, J = 16 Hz, 1 H), 3.65 (dq, J = 6, 6 Hz, 1 H), 3.25 (dq, J = 7.5, 6 Hz, 1 H), 1.18 (d, J = 7.5 Hz, 3 H), 1.09 (d, J = 6 Hz, 3 H). *cis*-1-Benzyl-3-ethyl-4-methylazetidinone (80%) was synthesized analogously: IR (CH_2Cl_2, cm^{-1}) 3096, 3041, 2974, 2939, 2882, 1740, 1501, 1458, 1437, 1408, 1388, 1359, 1239, 1193, 1152, 1141, 1070, 1031, 1004, 942, 821; ^1H NMR ($CDCl_3$) 7.31 (m, 5 H), 4.61 (d, J = 15.5 Hz, 1 H), 4.10 (d, J = 15.5 Hz, 1 H), 3.67 (dq, J = 6.6, 6.1 Hz, 1 H), 3.06 (ddd, J = 8, 8, 6.6 Hz, 1 H), 1.75 (ddq, J = 13.5, 8, 7.7 Hz, 1 H), 1.57 (ddq, J = 13.5, 8, 7.7 Hz, 1 H), 1.12 (d, J = 6.6 Hz, 3 H), 1.04 (t, J = 7.7 Hz, 3 H). Anal. Calcd for $C_{13}H_{17}NO$: C, 76.81; H, 8.43; N, 6.89. Found: C, 76.41; H, 8.29; N, 6.90. *cis*-1-Benzyl-3-benzyl-4-methylazetidinone (63%) was synthesized analogously: IR (CH_2Cl_2, cm^{-1}) 3095, 3039, 2976, 2924, 2861, 1739, 1608, 1499, 1452, 1435, 1405, 1383, 1359, 1238, 1148, 1122, 1078, 1029, 982, 948, 920; ^1H NMR ($CDCl_3$) 7.26 (m, 10 H), 4.64 (d, J = 15.7 Hz, 1 H), 4.13 nd, J = 15.7 Hz, 1 H), 3.72 (dq, J = 6.4, 5 Hz, 1 H), 3.57 (ddd, J = 9.3, 5.7, 5 Hz, 1 H), 3.19 (dd, J = 14.8, 5.7 Hz, 1 H), 2.86 (dd, J = 14.8, 9.3 Hz, 1 H), 1.12 (d, J = 6.4 Hz, 3 H). Anal. Calcd for $C_{17}H_{19}NO$: C, 80.60; H, 7.56; N, 5.53. Found: C, 80.69; H, 7.87; N, 5.20. *cis*-1-Benzyl-3-allyl-4-methylazetidinone (22%) was also synthesized analogously: IR (CH_2Cl_2, cm^{-1}) 3051, 2978, 2930, 1740, 1641, 1499, 1453, 1438, 1408, 1384, 1360, 1121, 1095, 1075, 1049, 1030, 921, 880, 848; ^1H NMR ($CDCl_3$) 7.39-7.22 (m, 5 H), 5.86 (dddd, J = 17.4, 8.7, 7.5, 5.6 Hz, 1 H), 5.17 (ddd, J = 17.4, 2, 1.5 Hz, 1 H), 5.06 (ddd, J = 8.7, 2, 1.5 Hz, 1 H), 4.61 (d, J = 15.2 Hz, 1 H), 4.10 (d, J = 15.2 Hz, 1 H), 3.71 (dq, J = 6.3, 5.7 Hz, 1 H), 3.26 (ddd, J = 9.6, 5.7, 5.2 Hz, 1 H), 2.53 (dddd, J = 15, 5.6, 5.2, 1.5 Hz, 1 H), 2.33 (dddd, J = 15, 9.6, 7.8, 1.5 Hz, 1 H), 1.13 (d, J = 6.3 Hz, 3 H); exact mass calcd for $C_{14}H_{17}NO$ 215.1310, found 215.1312.

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Supplementary Material Available: Stereoviews, tables of interatomic distances and bond angles, and tables of positional and thermal parameters for compounds **5** and **7** (19 pages); tables of calculated and observed structure factors (42 pages). Ordering information can be found on any current masthead page.

Total Synthesis of (±)-Poitediol and (±)-Dactylol

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Abstract: The unusual cyclooctanoid sesquiterpene, poitediol (**7**), was synthesized in racemic form in 20 steps from 2-methoxy-4-methyl-2-cyclohexen-1-one (**14**). The key step in the synthesis was the oxy-Cope rearrangement of 5-ethenyl-6-ethynyl-2-methylbicyclo[3.2.0]heptan-6-ol (**22**) to afford *cis*-1,2,3,3a,4,8-hexahydro-3-methyl-5*H*-cyclopentacycloocten-5-one (**10**). Racemic dactylol (**8**) was prepared in one step from poitediol by reduction with sodium in liquid ammonia.

The cyclooctanoid terpenes are a structurally diverse and potentially biologically important family of compounds. There are currently over 35 known natural products in this family, all of which are characterized by the presence of a cyclooctane fused to other carbocyclic rings. The first cyclooctanoid natural product to be isolated was the sesterterpene ophiobolin A (**1**), isolated from a plant pathogenic fungus.[1] Interestingly, ophiobolin A was the

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