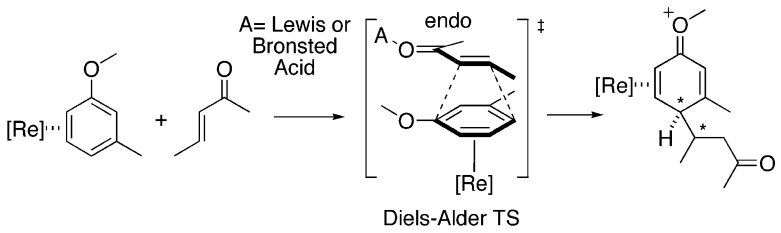
Article

Michael Addition Reactions with η6-Coordinated Anisoles: Controlling the Stereochemistry of the Para and Benzylic Carbons

Philip L. Smith, Joseph M. Keane, Sarah E. Shankman, Mahendra D. Chordia, and W. Dean Harman

J. Am. Chem. Soc., **2004**, 126 (47), 15543-15551• DOI: 10.1021/ja047054j • Publication Date (Web): 09 November 2004



More About This Article

Additional resources and features associated with this article are available within the HTML version:

- Supporting Information
- Links to the 1 articles that cite this article, as of the time of this article download
- Access to high resolution figures
- Links to articles and content related to this article
- Copyright permission to reproduce figures and/or text from this article

View the Full Text HTML

J|A|C|S
ARTICLES
Published on Web 11/09/2004

Michael Addition Reactions with η^2-Coordinated Anisoles: Controlling the Stereochemistry of the Para and Benzylic Carbons

Philip L. Smith, Joseph M. Keane, Sarah E. Shankman, Mahendra D. Chordia, and W. Dean Harman*

Contribution from the Department of Chemistry, University of Virginia, P.O. 400319, Charlottesville, Virginia 22904-4319

Received May 19, 2004; E-mail: wdh5z@virginia.edu

Abstract: Several η^2-coordinated anisole complexes were treated with various Michael acceptors in the presence of a Lewis or Brønsted acid to generate stable 4*H*-anisolium complexes. These reactions were found to proceed with high stereochemical control with predictable outcomes, provided that the moderate acid (NH_2Ph_2)OTf was used and the complex was dissolved in an acidic solution. The stereochemistry is shown to originate from an unexpectedly high preference for one coordination diastereomer of the anisole complex in the solid state and a Diels−Alder like transition state for the Michael reaction.

Introduction

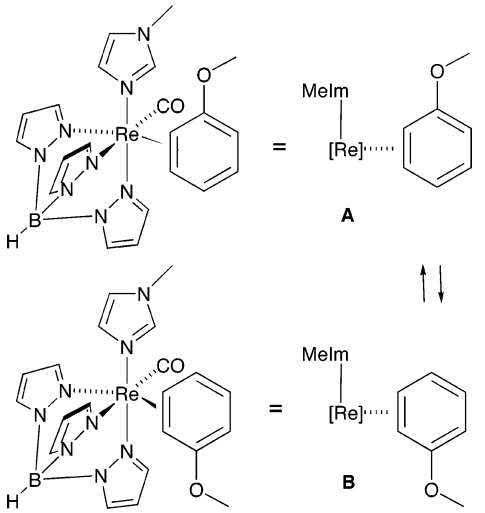
The alkylation of arenes is an important process that continues to receive a great deal of study. Of particular interest to medicinal chemists are those reactions that allow for stereocontrol at newly formed benzylic centers.[1,2] While Friedel−Crafts and related methodologies remain mainstays of organic synthesis,[3,4] they are typically plagued by a variety of problems, including multiple additions, poor regioselectivity, and harsh reaction conditions. These problems are avoided by approaches that involve metal coupling reagents, but most such reactions require prior functionalization (typically halogenation) of the arene reaction site.[5−8] Recently, some intriguing results have been reported on the application of arene C−H activation studies to C−C bond formation,[9−11] and investigations that extend the scope of this chemistry may result in effective alkylation strategies.

An alternative approach to arene alkylation relies on coordination of the arene to a transition metal.[12−14] In particular, our focus has been on arene transformations facilitated by η^2-coordination to a π-basic metal fragment. Significant π-electron donation from the metal to the bound arene renders the arene more nucleophilic and vastly expands the scope of reactions to which the arene is susceptible.[14] While the pioneering work in this area was carried out with pentaammineosmium(II),[15−17] a new series of dearomatizing metal fragments having the general form {TpM(π-acid)(L)} [Tp = hydridotris(pyrazolyl)borate, M = rhenium, molybdenum, or tungsten, π-acid = CO or NO, and L = a variable ligand] has recently been developed.[18−23] Some members of this series have demonstrated a greater ability than osmium(II) to activate aromatic molecules toward reaction with electrophiles.[23,24] Perhaps of greater significance, the

(1) Paras, N. A.; Macmillan: D. W. C. *J. Am. Chem. Soc.* **2002**, *124*, 7894−7895.
(2) Saaby, S.; Bayon, P.; Aburel, P. S.; Jorgenson, K. A. *J. Org. Chem.* **2002**, *67*, 4352−4361.
(3) Heaney, H. *Comprehensive Organic Synthesis*; Pergamon Press: Oxford, 1991; Vol. 2.
(4) Olah, G. A.; Krishnamurti, R.; Prakash, G. K. S. **1991**, *3*, 293−339.
(5) Knight, D. W. *Comprehensive Organic Chemistry*; Pergamon Press: Oxford, 1991; Vol. 3.
(6) Tamao, K. *Comprehensive Organic Chemistry*; Pergamon Press: Oxford, 1991; Vol. 3.
(7) Miyaura, N. S.; Akira, *Chem. Rev.* **1995**, *95*, 2457−2483.
(8) Beletskaya, I. P. C.; Andrei, V. *Chem. Rev.* **2000**, *100*, 3009−3066.
(9) Jia, C.; Lu, W.; Oyamada, J.; Kitamura, T.; Matsuda, K.; Irie, M.; Fujiwara, Y. *J. Am. Chem. Soc.* **2000**, *122*, 7252−7263.
(10) Jia, C.; Piao, D.; Oyamada, J.; Lu, W.; Kitamura, T.; Fujiwara, Y. *Science* **2000**, *287*, 1992−1995.
(11) Murai, S.; Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chanati, N. *Nature* **1993**, *366*, 529−531.
(12) Pape, A. R.; Kaliappan, K. P.; Kündig, E. P. *Chem. Rev.* **2000**, *100*, 2917−2940.
(13) Semmelhack, M. F. In *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon Press: Oxford, UK, 1995; Vol. 12, pp 979−1015.
(14) Kündig, E. P. *Transition Metal Arene π Complexes in Organic Synthesis and Catalysis*; Springer-Verlag: Berlin, 2004.
(15) Kopach, M. E.; Gonzalez, J.; Harman, W. D. *J. Am. Chem. Soc.* **1991**, *113*, 8972−8973.
(16) Kolis, S. P.; Kopach, M. E.; Liu, R.; Harman, W. D. *J. Org. Chem.* **1997**, *62*, 130−136.
(17) Harman, W. D. *Chem. Rev.* **1997**, *97*, 1953−1978.
(18) Gunnoe, T. B.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **1999**, *121*, 6499−6500.
(19) Gunnoe, T. B.; Sabat, M.; Harman, W. D. *Organometallics* **2000**, *19*, 728−740.
(20) Meiere, S. H.; Brooks, B. C.; Gunnoe, T. B.; Sabat, M.; Harman, W. D. *Organometallics* **2001**, *20*, 1038−1040.
(21) Meiere, S. H.; Brooks, B. C.; Gunnoe, T. B.; Carrig, E. H.; Sabat, M.; Harman, W. D. *Organometallics* **2001**, *20*, 3661−3671.
(22) Meiere, S. H.; Keane, J. M.; Gunnoe, T. B.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **2003**, *125*, 2024−2025.
(23) Graham, P.; Meiere, S. H.; Sabat, M.; Harman, W. D. *Organometallics* **2003**, *22*, 4364−4366.

10.1021/ja047054j CCC: $27.50

stereogenic metal is able to differentiate enantiofaces of the η^2-arene.

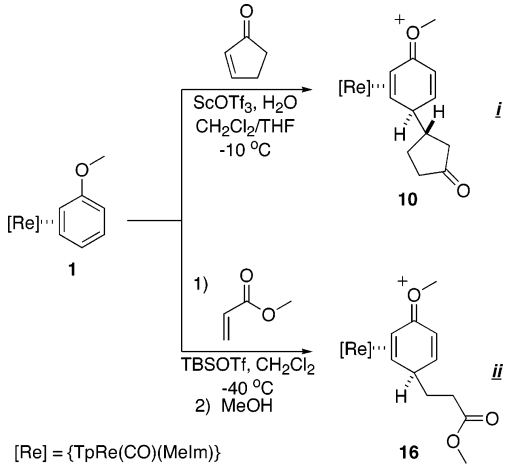


During the course of investigations of cycloaddition reactions of {TpRe(CO)(MeIm)(η^2-anisole)} and dienophiles,[24] an overwhelming preference for Michael-type additions over cycloadditions was observed when the reactions were performed under Lewis-acidic reaction conditions. Given the greater electron-donating ability of the {TpRe(CO)(MeIm)} fragment, it was hoped that these complexes would react under milder conditions than those used with pentaammineosmium(II) anisoles. Furthermore, in consideration of the chiral ligand environment for this rhenium system, we hoped to develop a strategy for controlling the absolute stereochemistry for these Michael addition reactions.

Results

In an initial study, TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**), TpRe(CO)(MeIm)(5,6-η^2-(3-methylanisole)) (**2**), and TpRe(CO)(MeIm)(5,6-η^2-(3-methoxyanisole)) (**3**) were screened with various Michael acceptors and Lewis acids under a variety of reaction conditions. Attempts to promote the model reaction of TpRe(CO)(MeIm)(η^2-anisole) (**1**) and MVK with triflic acid in acetonitrile (20 to −60 °C) caused rapid decomposition of the complex, yielding only traces of the 4*H*-anisolium product, while Zn(II), Yb(III), Ti(IV), Sn(II), anhydrous $Sc(OTf)_3$, or TBSOTf (with MVK and other conjugated ketones) resulted in either no reaction, oxidation, or intractable mixtures of products. The use of $BF_3{\cdot}OEt_2$ was more promising, with varying amounts of the desired addition product being observed along with other unidentified material. However, compounds **1**−**3** were found to readily undergo conjugate addition reactions with a number of α,β-unsaturated carbonyl compounds in the presence of either $Sc(OTf)_3$[25−27] or TBSOTf. For *N*-methylmaleimide and conjugated ketones, wet $Sc(OTf)_3$ promoted conjugate addition and protonation of the resulting enolate to afford 4*H*-anisolium complexes (e.g., Scheme 1, reaction i). Similarly, the less reactive electrophile methyl acrylate reacted when TBSOTf was employed, yielding the 4*H*-anisolium complex **16** (Scheme 1, reaction ii). In a typical reaction sequence, the arene complex and Michael acceptor were combined and cooled (−10 °C for reactions with $Sc(OTf)_3$ or −40 °C for that with TBSOTf), and then the Lewis acid was added at low temperature. The resulting 4*H*-anisolium complexes were isolated by precipitation into Et_2O/hexanes (1:1). Results for the reactions of **1**, **2**, and **3** with various Michael acceptors are summarized in Table 1. Yields of the resulting anisolium salts (**5**−**16**) were high, but the purity of these compounds, as determined by combustion analysis, was found to be unsatisfactory, presumably due to residual Lewis acid and decomposition products (vide infra). While the facial diastereoselectivity of the products (**A:B**) reflected the low diastereomeric ratio of the initial solvated anisole complexes, significant diastereocontrol at the latent benzylic position (endo: exo, vide infra) was observed in several examples.

Scheme 1. Two Michael Addition Reactions of TpRe(CO)(MeIm)(5,6-η^2-anisole) (1)

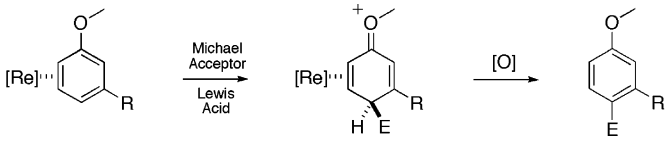


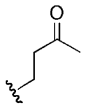
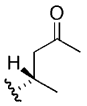
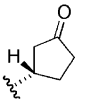
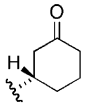
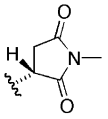
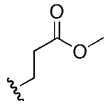
The extremely low solubility of the {TpRe(CO)(MeIm)} anisole complexes in a variety of common organic solvents has been previously documented.[28] In the current study, this low solubility led to difficulty obtaining complete conversion in the synthesis of TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**), TpRe(CO)(MeIm)(5,6-η^2-(3-methylanisole)) (**2**), and TpRe(CO)(MeIm)(5,6-η^2-(3-methoxyanisole)) (**3**) and limited the range of reaction solvents in which these complexes could be dissolved. (The above investigations were typically carried out in solutions of THF and methylene chloride). For these reasons, further investigations were carried out using the TpRe(CO)(BuIm)(5,6-η^2-anisole) (**4**) analogue. The greater solubility of the *N*-butylimidazole variant (**4**) allowed for both facile preparations of pure samples and a much wider range of reaction solvent conditions.

During the course of protonation studies with the TpRe(CO)(RIm)(η^2-anisole) complexes, we discovered that moderately strong Brønsted acids such as protonated alcohols or arylammonium salts could be used to form anisolium complexes with good stereocontrol (**A**:**B**).[28] It was hypothesized that a moderate acid could be used to reversibly capture one coordination diastereomer of the anisole complex (as a 2*H*-anisolium) and then to promote a Michael addition reaction at a sufficiently high rate that the stereochemistry of coordination is conserved (Scheme 2).

(24) Chordia, M. D.; Smith, P. L.; Meiere, S. H.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **2001**, *123*, 10756−10757.
(25) Kobayashi, S.; Hachiya, I.; Ishitani, H.; Araki, M. *Synlett* **1993**, 472−474.
(26) Kobayashi, S. *Synlett* **1994**, 689−701.
(27) Kobayashi, S. *Eur. J. Org. Chem.* **1999**, 15−27.
(28) Keane, J. M.; Chordia, M. D.; Mocella, C. J.; Sabat, M.; Trindle, C. O.; Harman, W. D. *J. Am. Chem. Soc.* **2004**, *126*, 6806−6815.

Table 1. Michael Additions of {TpRe(CO)(MeIm)} Anisole Complexes

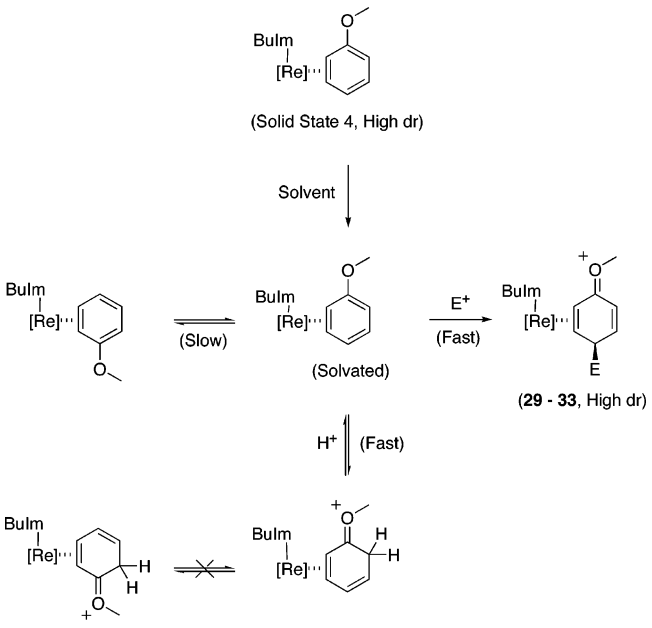


Item	R	E	Anisolium	dr (A:B)[a]	dr (endo:exo)[b]	Anisole	Yield %[c]
1	H		**5**	1.4:1	--	**17**	83
2	Me		**6**	3:1	--	**18**	33
3	OMe		**7**	1:1	--	**19**	52
4	H		**8**	1:2	8:1	**20**	68
5	Me		**9**	1:1	10:1	**21**	25
6	H		**10**	1:1	16:1	**22**	42
7	Me		**11**	3:5	5:3	**23**	25
8	H		**12**	1:1	>20:1	**24**	68
9	Me		**13**	1:1	1:1	**25**	20
10	H		**14**	1:1	>20:1	**26**	70
11	Me		**15**	3:1	3:1	**27**	14
12	H		**16**	1:1	--	**28**	87

[a] The diastereomeric ratio **A**:**B** in the isolated anisolium products as determined by ^{1}H NMR. [b] Stereoselectivity at the benzylic carbon regardless of the orientation of the ligand with respect to the metal fragment; in each case, the major isomer is thought to have an endo-configuration, but this outcome has been confirmed only for complex **14**. [c] The overall yield of the net aromatic substitution product from arene complex **1**, **2**, or **3**.

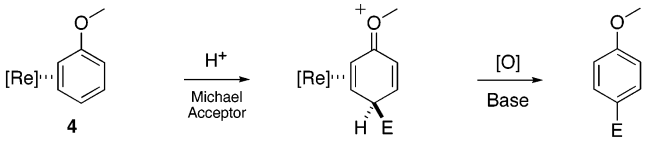
Indeed, when solutions of various Michael acceptors were added to mixtures of TpRe(CO)(BuIm)(5,6-η^2-anisole) (**4**) and diphenylammonium triflate, additions occurred to give highly diastereoselective anisolium products that could be isolated, in high yields and in analytically pure forms, by precipitation into hexanes following aqueous extraction. Results for reactions of **4** with various Michael acceptors are detailed in Table 2. Facial diastereoselectivity of anisolium complexes **29**−**33** was uniformly high (>20:1 **A**:**B**), as long as the initial complexes were dissolved in the presence of the acid. Alternatively, when TpRe(CO)(BuIm)(5,6-η^2-anisole) (**4**) was first dissolved at ambient temperature and then exposed to acid and cyclopenten-2-one, the resulting anisolium (**31**) showed only 4:1 diastereoselectivity (**A**:**B**).

Scheme 2. Mechanism Proposed To Be Responsible for the High Degree of Facial Diastereoselectivity (A:B) Observed in Anisolium Products **29**−**33**

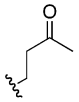
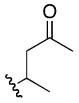
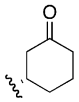
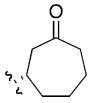


Spectroscopic features of {TpRe(CO)(RIm)} 4*H*-anisolium complexes **5**−**16** and **29**−**33** include bound olefinic resonances that appear as broad doublets (J_{HH} = 7.5) between 3.4 and 5.0 ppm in the ^{1}H NMR spectrum. The ^{13}C NMR spectra of these complexes feature resonances at ∼187 ppm (C1), ∼70 ppm (C5), and ∼60 ppm (C6). Facial diastereomers of **5**−**16** and **29**−**33** (**A**:**B**) were assigned on the basis of established trends in the chemical shifts of protons at the bound positions.[20,21,24] These assignments are supported by a one-dimensional NOE study of [TpRe(CO)(MeIm)(4β-(2-(methoxycarbonyl)ethyl)-5α,6α-η^2-(4*H*-anisolium))](OTf) (**16**) (Figure 1). Irradiation of the downfield oxonium methoxy protons of diastereomer A (δ 3.55) resulted in enhancement of two imidazole resonances, whereas irradiation of the upfield oxonium methoxy protons of

Table 2. Michael Additions of TpRe(CO)(BuIm)(5,6-η^2-anisole) (4)



[Re] = {TpRe(CO)(BuIm)}

Item	E	Anisolium	Yield %[a]	dr (A:B)[b]	dr (endo:exo)[c]	Product	Yield %[d]
1		**29**	89	>20:1	-	**17**	66
2		**30**	88	>20:1	7.5:1	**20**	79
3		**31**	88	>20:1	>20:1	**22**	53
4		**32**	92	>20:1	>20:1	**24**	51
5		**33**	90	>20:1	11:1	**34**	54

[a] Yield of the isolated anisolium complex from **4**. [b] The diastereomeric ratio **A**:**B** in the isolated anisolium products as determined by ^{1}H NMR. [c] Stereoselectivity at the benzylic carbon regardless of the orientation of the ligand with respect to the metal fragment; in each case, the major isomer is thought to have an endo-configuration, but this outcome has been confirmed only for complex **14**. [d] The overall yield of the net aromatic substitution product from arene complex **4**.

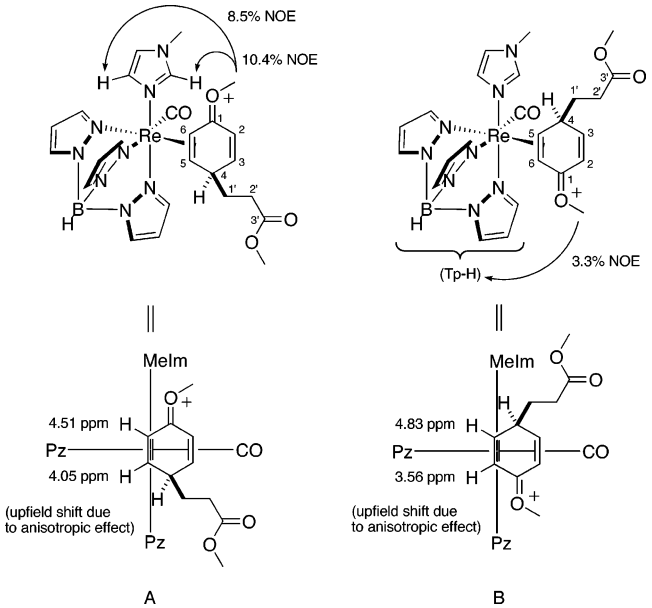


Figure 1. Data used to assign the **A**:**B** isomers of [TpRe(CO)(MeIm)(4β-(2-(methoxycarbonyl)ethyl)-5α,6α-η^2-(4*H*-anisolium))](OTf) (**16**).

diastereomer **B** (δ 3.06) provided enhancement of a single Tp resonance. Additionally, for isomer **16B**, irradiation of H4 resulted in enhancement of two imidazole signals. Stereoisomers of **5**−**16** and **29**−**33** differing in configuration at the latent benzylic position are designated as endo if the observed stereochemical outcome presumably resulted from an endo transition state arrangement of the Michael acceptor with respect to the unbound portion of the aromatic ring (vide infra). The alternative configuration is designated as exo. An authentic sample of **14-*endo*** was prepared through an acid-promoted retro-Aldol type ring-opening of the *N*-methylmaleimide cycloadduct of TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**) (complex **35**, vide infra; Scheme 3). The ^{1}H NMR spectra of the Michael addition product assigned as **14-*endo*** matched that of an authentic sample.

Anisolium complexes **5**−**16** and **29**−**33** were found to be unstable to silica and alumina, but they were stable to water and more resistant to thermal degradation than the previously reported pentaammineosmium(II) analogues.[16] The {TpRe(CO)(RIm)}-bound anisoliums remained intact for several weeks when stored as solids at ambient temperature. When samples of **5**−**16** and **29**−**33** were allowed to stand in solution at ambient temperature, the formation of 4-alkylanisoles was typically observed over a period of days. Remarkably, the rate of formation of **17**−**28** and **34** was not significantly affected by the presence of amine bases such as DIEA or pyridine, indicating a high kinetic barrier for deprotonation at C4. The use of stronger bases such as NaH, NaOMe, and LiHMDS resulted in retro-Michael reactions, from which the parent anisole complexes were isolated. Oxidation using $CuBr_2$ proved to be an effective strategy for decomplexation with concomitant rearomatization. Exposure to air, heat, trifluoroacetic acid, or sodium bicarbonate proved to further facilitate this process, and 4-alkylanisoles **17**−**28** and **34** were isolated with typical overall yields

ranging from 50 to 85% starting from the TpRe(CO)(RIm)-(arene) complexes (Tables 1 and 2).

Discussion

The {TpRe(CO)(RIm)} metal fragments bind an anisole preferentially across C5−C6, rendering the π-bonds of the uncoordinated portion of the arene ligand partially localized. Due to the electron-donating properties of the methoxy group, the π-system is polarized so that the most nucleophilic positions are C2 and C4. However, the approach to C2 is hindered by the methoxy group, which must lie in the plane of the ring, but away from the metal. Thus, the addition of Michael-type electrophiles is observed only at C4. This regiochemistry is consistent with that observed for Michael reactions of pentaammineosmium(II)(η^2-anisole) complexes.[16]

Michael additions of pentaammineosmium(II)(η^2-anisole) complexes were successfully performed, but under more acidic conditions using HOTf in acetonitrile as a promoter. Similar conditions were ineffective with the second-generation {TpRe-(CO)(RIm)} anisole complexes, presumably because these rhenium fragments are more susceptible to oxidation of the metal center. This study of TpRe(CO)(RIm)(η^2-anisole) complexes has shown that the arene ligand is more activated toward electrophilic addition than that of the pentaammineosmium(II) analogues,[24,26] though also more easily oxidized by acid. This greater degree of arene activation is manifested by the ability to promote Michael additions using acids that are nearly 11 orders of magnitude weaker than those utilized with pentaammineosmium(II) ($\sim pK_a$ −10 for CH_3CNH^+ vs $\sim pK_a$ 0.8 for $Ph_2NH_2^+$). Given the observed disparity in the results of {TpRe-(CO)(MeIm)} anisole reactions promoted with water and Sc-$(OTf)_3$ and those attempted with anhydrous $Sc(OTf)_3$, it is possible that in the synthesis of anisoliums **5**−**16**, the lanthanide salt/water combination functioned primarily as a proton source.

Michael addition reactions with TpRe(CO)(RIm)(η^2-anisole) occur with control of up to three stereogenic centers (counting the two bound carbons as a single stereocenter). While the parent arene complexes (**1**−**4**) typically exhibit low facial diastereoselectivity in equilibrated solutions (2:1 ratio of **A**:**B**), both the TpRe(CO)(RIm)(arene) complexes and their conjugate acids have been observed in significantly higher (up to >20:1) diastereomeric ratios.[29] Spectroscopic data of solutions generated at low temperature (−40 to −80 °C) have conclusively demonstrated that {TpRe(CO)(L)} arene complexes in the solid state exist as much higher ratios of coordination diastereomers than are typically observed in solutions at ambient temperature.[30] It is thought that under the reaction conditions used in the synthesis of anisolium complexes **29**−**33**, TpRe(CO)(BuIm)-(5,6-η^2-anisole) (**4**) is protonated at a rate much greater than that at which coordination isomerizations of the arene ligand occur. The resulting anisolium species is a stronger π-acid than the initial arene, and both substitution and isomerization rates are expected to be dramatically reduced. Thus, the diastereoselectivity that is initially present in the solid state is trapped in solution by rapid protonation (Scheme 2).[30] Since a high degree of facial diastereoselectivity (**A**:**B**) is observed in Michael adducts **29**−**33**, it is reasonable to conclude that, *upon deprotonation of the anisolium*, reaction of **4** with the Michael acceptor is also a much faster process than the facial isomerizations of the arene ligand. *4H-Anisolium* complexes having a high degree of facial diastereoselectivity are therefore formed from samples of TpRe(CO)(BuIm)(5,6-η^2-anisole) (**4**), which exist in high diastereomeric ratios carried over from the solid state (see Scheme 2).[30]

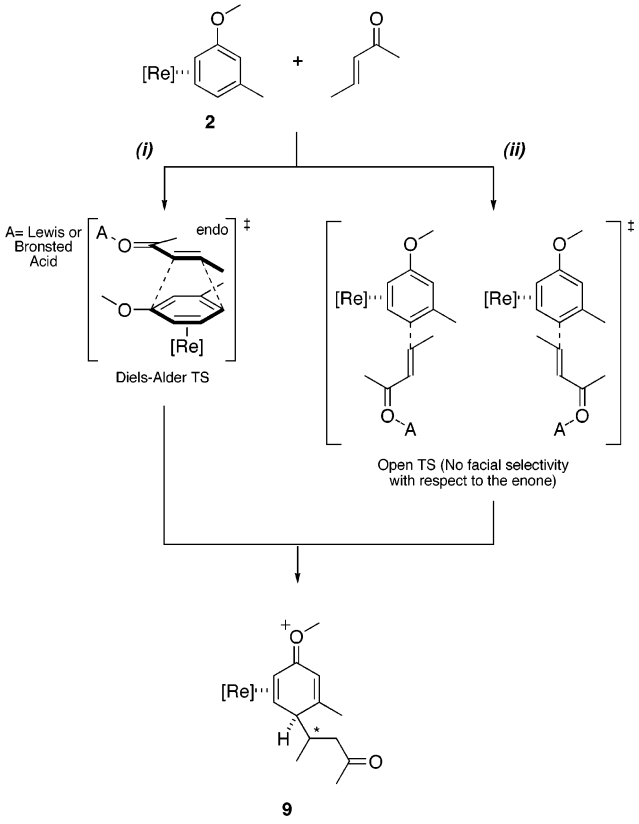


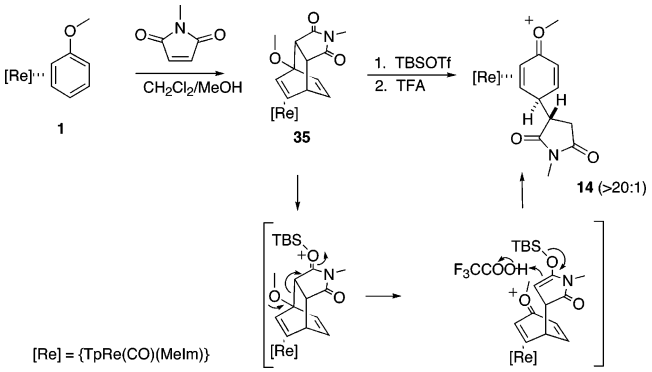
Figure 2. Transition state representations for the acid-catalyzed Michael addition of TpRe(CO)(MeIm)(5,6-η^2-(3-methylanisole)) (**2**) to 3-penten-2-one.

The addition of a carbon electrophile to C4 of TpRe(CO)-(RIm)(anisole) complexes generates a stereogenic center at this position. Consistent with all previous examples of electrophilic additions to TpRe(CO)(L)(naphthalene) and pentaammineosmium-(II) arene complexes,[17,31] the Michael acceptors approach the bound arenes exclusively from the unbound arene face, selectively setting the stereochemistry at C4. Evidence for this pathway includes the observed NOE effect on imizadole signals upon irradiation of the H4 proton of [TpRe(CO)(MeIm)(4β-(2-(methoxycarbonyl)ethyl)-5α,6α-η^2-(4*H*-anisolium))](OTf) (**16B**) (vide supra).

When β-substituted Michael acceptors react with a bound anisole, a stereogenic center is formed at the latent benzylic position (formally C1′ for all anisolium complexes except **14** and **15**, for which this position is designated as C4′). The high stereoselectivity observed [Tables 1 and 2, dr (endo:exo)] suggests the presence of an ordered transition state. Figure 2 shows two possible reaction pathways for the acid-catalyzed Michael addition of TpRe(CO)(MeIm)(5,6-η^2-(3-methylanisole)) (**2**) to 3-penten-2-one. On the left, (**i**) is a transition state

(29) Valahovic, M. T.; Gunnoe, T. B.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **2002**, *124*, 3309−3315.
(30) Keane, J. M.; Ding, F.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **2003**, *126*, 785−789.
(31) Valahovic, M. T.; Keane, J. M.; Harman, W. D. In *Modern Arene Chemistry*; Astruc, D., Ed.; Wiley-VCH Verlag GmbH & KGaA: Weinheim, 2002, pp 297−329.

Scheme 3. Diels−Alder Reaction of TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**) and Retro-Aldol Ring Opening of the Resulting Cycloadduct (**35**)



resembling that for an endo-Diels−Alder reaction, which would lead to **9** with predictable stereocontrol at the latent benzylic carbon (labeled with an asterisk). Conversely, the open transition state **ii** would not be expected to afford high stereoselectivity at this position.

In a recent communication,[24] it was reported that TpRe(CO)(MeIm)(η^2-benzene) undergoes an endo-selective Diels−Alder reaction with NMM to generate the corresponding endo-adduct exclusively. In a similar manner, TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**) reacts to form a cycloadduct, isolated as two coordination diastereomers, in which the methoxy group is in a bridgehead position (Scheme 3). The isomer arising from coordination diastereomer **1A** (**35A**) was separated from **35B** by chromatography and then treated with TBSOTf in the presence of TFA to afford a sample of anisolium complex **14A** with identical stereochemistry to that generated by the acid-catalyzed Michael addition pathway (^{1}H NMR).

For Michael addition reactions involving TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**), the hypothesized Diels−Alder-like reaction pathway in Figure 2 is most consistent with the high stereoselectivity observed at the latent benzylic carbon. A similar explanation has been invoked with highly diastereoselective Mukaiyama Michael[32,33] and Mukaiyama aldol[34−36] reactions. In contrast, Michael reactions with TpRe(CO)(MeIm)(5,6-η^2-(3-methylanisole)) (**2**), which show poor stereocontrol, are likely to proceed through the more conventional open transition state (**ii**), typical of a standard Mukaiyama Michael addition.[37,38] The presence of the additional methyl group in **2** is expected to disfavor a Diels−Alder-like reaction pathway in two ways. The 3-methyl substituent should cause steric strain in the endo transition state for cis, but not trans, substituted Michael acceptors. Thus, the Michael addition of **1** to cyclohexenone (Table 1, item 6) yields a dr of >20:1 (endo/exo), whereas the analogous addition of the 3-methyl analogue (**2**; Table 1, item 7) affords a dr of only 1:1. However, when the trans-substituted olefin 3-penten-2-one (Table 1, item 9) is used, the steric strain between methyl groups is negligible for the purported endo-approach and the dr is again high (10:1). In addition to the steric factor, a methyl group situated at the 3-position of the bound anisole can stabilize the competing open transition state through hyperconjugation. A direct electrophilic addition at C4 would result in some 4*H*-anisolium character in the transition state and, therefore, a buildup of positive charge at C3.

The high stereocontrol of the latent benzylic carbon afforded by these rhenium anisole complexes is typically not realized in the analogous osmium(II) chemistry. Whereas reactions with the TpRe(CO)(RIm)(η^2-anisole) complexes are likely to be influenced by orbital interactions (vide supra), Michael reactions that were carried out with pentaammineosmium(II) anisole complexes required highly acidic reaction conditions and likely have open transition states that are dominated by charge−charge interactions. In the original pentaammineosmium(II)(η^2-anisole) study with Michael acceptors, triflic acid in acetonitrile was required for the reactions to occur. Due to low thermal stability of the resulting 4*H*-anisolium species, rearomatized 4-alkylated anisole complexes were isolated.[16] While high diastereoselectivities were observed for these complexes, a follow-up study utilizing a remote chiral center[39] showed this stereoselectivity to be the result of linkage isomerizations of the metal fragment, *after* the Michael addition. The selectivity in the Michael reaction itself was found in most cases to be poor.[39]

In special cases, success in controlling the stereochemistry of the benzylic position has been realized using pentaammineosmium(II). A reaction with *N*-methylmaleimide and [Os(NH$_3$)$_5$(η^2-anisole)]$^{2+}$ in the presence of BF_3·OEt_2 gave the corresponding 4*H*-anisolium complex.[40] Under kinetic conditions, this anisolium was shown to cyclize to give a bicyclooctadiene complex having endo-stereochemistry similar to **35**. Yet, the possibility of linkage isomerizations occurring after the Michael addition could not be excluded, so the final orientation of the cycloadduct did not provide strong evidence of selectivity in the initial addition reaction. Also relevant to this discussion are conjugate addition reactions reported for phenol complexes of pentaammineosmium(II).[15,41] In contrast to the osmium−anisole Michael reactions, those with phenol were carried out under mildly basic reaction conditions. The isolated 4-substituted dienone products showed a high degree of diastereoselectivity at the latent benzylic carbon. While the putative cycloadduct intermediate could not be isolated, the high dr was hypothesized to result from the formation of an endo-selective Diels−Alder cycloadduct intermediate.

With a viable strategy in hand to control the stereochemistry of the organic ligand relative to that of the transition metal, one could imagine controlling the absolute stereochemistry of the 4*H*-anisolium ligand (and, thus, the 4-substituted anisole), provided that the reaction sequence was carried out with an enantio-enriched form of the rhenium. In a recent report, a resolved form of TpRe(MeIm)(η^2-benzene) was prepared using α-pinene.[42] However, the observation that a compound forms a stereoselective solid phase as a racemic mixture does not guarantee the same result for the corresponding enantio-enriched

(32) Evans, D. A.; Scheidt, K. A.; Johnston, J. N.; Willis, M. C. *J. Am. Chem. Soc.* **2001**, *123*, 4480−4491.
(33) Talan, L. A.; Poon, C. D.; Evans, S. A. J. *J. Org. Chem.* **1996**, *61*, 7455−7462.
(34) Danishefsky, S. J.; Larson, E.; Askin, D.; Kato, N. *J. Am. Chem. Soc.* **1985**, *107*, 1246−1255.
(35) Birkinshaw, T. N.; Tabor, A. B.; Holmes, A. B.; Kaye, P.; Mayne, P. M.; Raithby, P. R. *J. Chem. Soc. Chem. Commun.* **1988**, 1599−1601.
(36) Birkinshaw, T. N.; Tabor, A. B.; Holmes, A. B.; Raithby, P. R. *J. Chem. Soc. Chem. Commun.* **1988**, 1599−1601.
(37) Oare, D. H.; Heathcock, C. H. *Top. Stereochem.* **1991**, *21*, 227.
(38) Narasaki, K.; Soai, K.; Mukaiyama, T. *Chem. Lett.* **1974**, 1223−1224.
(39) Chordia, M. D.; Harman, W. D. *J. Am. Chem. Soc.* **2000**, *122*, 2725−2736.
(40) Kopach, M. E.; Harman, W. D. *J. Org. Chem.* **1994**, *59*, 6506−6507.
(41) Kopach, M. E.; Harman, W. D. *J. Am. Chem. Soc.* **1994**, *116*, 6581−6592.
(42) Meiere, S. H.; Valahovic, M. T.; Harman, W. D. *J. Am. Chem. Soc.* **2002**, *124*, 15099−15103.

material. If the racemate organizes in a centrosymmetric space group in the solid, this state will not be possible for the enantio-enriched form. For example, consider the anisole complex **1**, which, despite its 2:1 equilibrium ratio, precipitates in hexanes to form a solid containing >95% diastereomer **A**. When an enantio-enriched sample of **1** was precipitated in the same manner, protonation experiments showed the resulting solid to contain only a 3:1 ratio of **A**:**B**.[28,30] Thus, the present system does not appear to not be amenable to the efficient preparation of enantio-enriched para-alkylated anisoles.

The difficulty in effecting rearomatization of anisoliums **5**−**16** and **29**−**33** through simple deprotonation may be ascribed to both the high degree of steric bulk surrounding the C4-proton and the stabilization afforded the anisolium through π-electron donation from the metal. The proton is blocked on one face by the ligands of the metal center and on the other face by the newly added alkyl chain of the Michael acceptor. In addition, the greater π-electron donation involved in {TpRe(CO)(RIm)} anisolium complexes makes these species significantly less acidic than the analogous pentaammineosmium(II) anisoliums, which are readily deprotonated by amine bases.[16] It is speculated that the stability of **5**−**16** and **29**−**33** to moderately strong bases may allow for reactions of these anisolium complexes with stronger nucleophiles than those that were employed with the analogous pentaammineosmium(II) species.

Experimental Section

General Methods. Unless otherwise noted, all synthetic reactions and electrochemical experiments were performed under a dry nitrogen atmosphere. Preparative thin-layer chromatography (TLC) was performed on Uniplate silica gel GF or alumina GF plates from Analtech Inc. CH_2Cl_2, benzene, tetrahydrofuran (THF), and hexanes were purged with nitrogen and purified by passage through a column packed with activated alumina.[43] Other solvents and liquid reagents were thoroughly purged with nitrogen prior to use. Deuterated solvents were used as received from Cambridge Isotopes. Compounds TpRe(CO)(MeIm)(η^2-benzene),[20,21,24] **1**,[21] **2**,[24] **3**,[24] **4**,[24] **17**,[16] **20**,[16] **22**,[44] **24**,[16,44] **26**,[44] **27**,[16] and **35**,[24] have been previously reported.

General Procedure for TpRe(CO)(RIm)(η^2-anisole) Complexes 1−**4.** The anisole complexes were prepared using the procedure of Meiere. [21] In a typical procedure, TpRe(CO)(RIm)(η^2-benzene) (1.2 g, 2 mmol) is dissolved in THF (~5 mL), and then the solution is diluted with the desired anisole (10 mL) and stirred 72 h at 25 °C. The resulting precipitate is collected on a fine frit, washed with hexanes (3 × 5 mL), and dried in vacuo. Typical yields are >85%.

Compounds 5−**15 were synthesized as follows**: Two solutions, the first consisting of a {TpRe(CO)(MeIm)} anisole complex (1.0×10^{-4} mol) and a Michael acceptor (5.0×10^{-4} mol) dissolved in CH_2Cl_2 (4.4 g) and the second consisting of $Sc(OTf)_3$ (1.1×10^{-4} mol) dissolved in THF and water (6.0 mL of a 1.6% v/v solution of water in THF), were chilled to −10 °C and then combined. An immediate color change from pale yellow to dark red/orange was observed. The reaction was monitored by recording an infrared spectra of aliquots of the reaction treated with pyridine (Re-anisole $\nu_{C\equiv O} = 1797$ cm^{-1}). When all the starting material was consumed, the reaction mixture was transferred to a round-bottomed flask, and volatiles were removed under reduced pressure. The resulting residue was rinsed with ~1:1 Et_2O/hexanes (3 × 10 mL), dissolved in DME (~3 mL), and added to a stirring solution of hexanes/Et_2O (100 mL, 1:1). The solution was chilled for ~5 min by solvent evaporation under reduced pressure, and the resulting precipitate was collected on a fine frit, washed with hexanes (3 × 1 mL), and dried in vacuo to yield a brown solid.

Anisolium regiochemistry is designated by considering the metal to be bound across C5 and C6. Facial diastereomers are designated as **A** if the 1-position methoxy group is directed toward the imidazole ligand and as **B** if the 1-position methoxy group is directed away from the imidazole ligand. Stereiosomers designated as endo are those thought to have resulted from an endo transition state arrangement of the Michael acceptor with respect to the unbound portion of the aromatic ring. The alternative configuration is designated as exo. The accuracy of this designation is certain only for complex **14**. Anisolium complexes **5**−**16** and **29**−**33** were unstable to purification on silica or alumina, and attempts to crystallize the products were unsuccessful. Yields of these complexes are reported only for those that were isolated in analytically pure forms.

[TpRe(CO)(MeIm)(4*β*-(3-oxocyclopentyl)-5α,6α-η^2-(4*H*-anisolium))](OTf) (10). Reaction time was 12 h. This compound was isolated as a mixture of isomers in a ratio of 1:2 **A**:**B** and 16:1 **endo**:**exo**. ^{1}H NMR (acetone-d_6, ambient temperature, δ): minor diastereomer (**10A-*endo***), 8.17 (1H, d, J = 2.0, Tp 3,5), 8.11 (1H, buried, Tp 3,5), 7.99 (1H, d, J = 2.0, Tp 3,5), 7.92 (1H, d, J = 2.0, Tp 3,5), 7.84 (1H, buried, Tp 3,5), 7.82 (1H, bs, Im), 7.47 (1H, d, J = 2.0, Tp 3,5), 7.32 (1H, bs, Im), 7.18 (1H, m, H3), 6.70 (1H, d, J = 9.9, H2), 6.58 (1H, buried, Im), 6.55 (1H, buried, Tp 4), 6.36 (1H, t, J = 2.0, Tp 4), 6.14 (1H, t, J = 2.0, Tp 4), 4.57 (1H, d, J = 7.4, H6), 4.21 (1H, d, J = 7.4, H5), 3.90 (3H, s, NCH_3), 3.60 (1H, buried, H4), 3.57 (3H, s, OCH_3), 2.56−1.46 (7H, several m, H1′, 2 × H2′, 2 × H4′, and 2 × H5′) (BH not observed); minor diastereomer (**10A-*exo***), 4.13 (1H, d, J = 7.4, H5); major diastereomer (**10B-*endo***), 8.26 (1H, d, J = 2.0, Tp 3,5), 8.11 (1H, d, J = 2.0, Tp 3,5), 8.10 (1H, d, J = 2.0, Tp 3,5), 7.83 (1H, d, J = 2.0, Tp 3,5), 7.54 (1H, d, J = 2.0, Tp 3,5), 7.40 (1H, d, J = 2.0, Tp 3,5), 7.29 (1H, bs, Im), 7.01 (1H, ddd, J = 10.6, 4.8, 1.6, H3), 6.75 (1H, bs, Im), 6.58 (1H, t, J = 2.0, Tp 4), 6.55 (1H, bs, Im), 6.54 (1H, buried, H2), 6.45 (1H, t, J = 2.0, Tp 4), 6.15 (1H, t, J = 2.0, Tp 4), 4.89 (1H, d, J = 7.5, H5), 3.90 (3H, s, NCH_3), 3.64 (1H, d, J = 7.5, H6), 3.37 (1H, m, H4), 3.06 (3H, s, OCH_3), 2.56−1.46 (7H, several m, H1′, 2 × H2′, 2 × H4′, and 2 × H5′) (BH not observed); minor diastereomer (**10B-*exo***), 4.82 (1H, d, J = 6.7, H5). ^{13}C NMR (acetone-d_6, ambient temperature, δ): minor diastereomer (**10A-*endo***), 216.8 (C3′), 196.1 (CO), 187.3 (C1), 151.6 (C3), 144.6 (Tp 3,5), 144.2 (Tp 3,5), 143.1 (Tp 3,5), 141.1 (Tp 3,5), 138.5 (Tp 3,5), 138.0 (Tp 3,5), 136.2 (Im), 124.1 (Im), 123.8 (Im), 119.5 (C2), 108.1 (Tp 4), 107.7 (Tp 4), 107.4 (Tp 4), 67.2 (C5), 58.2 (OCH_3 or C6), 57.7 (OCH_3 or C6), 48.8 (C4), 45.0 (C1′), 42.5 (C2′), 38.3 (C4′), 35.0 (NCH_3), 27.9 (C5′); major diastereomer (**10B-*endo***), 217.1 (C3′), 194.9 (CO), 186.2 (C1), 150.8 (C3), 148.2 (Tp 3,5), 144.3 (Tp 3,5), 142.2 (Tp 3,5), 140.9 (Tp 3,5), 139.2 (Tp 3,5), 137.8 (Tp 3,5), 136.9 (Im), 130.1 (Im), 124.0 (Im), 123.6 (C2), 109.0 (Tp 4), 108.2 (Tp 4), 107.5 (Tp 4), 69.4 (C5), 59.3 (C6), 58.0 (OCH_3), 50.0 (C4), 43.7 (C1′), 42.1 (C2′), 38.5 (C4′), 35.0 (NCH_3), 26.8 (C5′). IR: ν_{BH} = 2496 cm^{-1} (vw), $\nu_{C\equiv O}$ = 1852 cm^{-1} (s), $\nu_{C=O}$ = 1704 cm^{-1} (s). CV: $E_{p,a}$ = 1.05 V, $E_{p,c}$ = −1.00 V. Anal. Calcd for $C_{27}H_{31}BF_3N_8O_6ReS$: C, 38.17; H, 3.68; N, 13.33. Found: C, 37.84; H, 3.34; N, 13.33.

Compound 16. Two solutions, the first consisting of TpRe(CO)(MeIm)(5,6-η^2-anisole) (**1**, 0.06 g, 1×10^{-4} mol) and methylacrylate (0.09 g, 1×10^{-3} mol, predried by passing through a plug of anhydrous alumina or by stirring with activated alumina then filtering) dissolved in CH_2Cl_2 (4.4 g) and the second consisting of TBSOTf (0.029 g, 1.1×10^{-4} mol, predried by passing through a plug of anhydrous alumina) dissolved in CH_2Cl_2 (0.5 g), were chilled to −40 °C and combined. An immediate color change was observed from pale yellow to dark red/orange. The reaction was monitored by electrochemistry or IR (**1**; $\nu_{C\equiv O}$ = 1797 cm^{-1}) with the IR aliquot being first quenched with base (TEA, DIEA, or NH_3/MeOH). When all the starting material was consumed (~20 min), cold (−40 °C) methanol (0.5 mL) was added and the reaction was stirred for an additional 10 min. The reaction

(43) Pangborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, *15*, 1518−1520.
(44) Jones, P.; Reddy, C. K.; Knochel, P. *Tetrahedron* **1998**, *54*, 1471−1490.

mixture was transferred to a round-bottomed flask, and volatiles were removed under reduced pressure. The residue was rinsed with hexanes (3 × 10 mL). The remaining red oil was dissolved in DME (~3 mL) and added to a stirring solution of hexanes/Et_2O (100 mL, 1:1). The mixture was chilled by applying a vacuum for ~5 min, and the resulting precipitate was collected on a fine frit, washed with hexanes (3 × 1 mL), and dried under vacuum.

[TpRe(CO)(MeIm)(4*β*-(2-(methoxycarbonyl)ethyl)(5α,6α-η^2-(4*H*-anisolium))](OTf) (16). This compound was isolated as a 1:1 mixture of **16A** and **16B**. ^{1}H NMR (acetone-d_6, ambient temperature, δ): **16A**, 8.13 (2H, d, J = 2.0, 2 × Tp 3,5), 7.98 (1H, d, J = 2.0, Tp 3,5), 7.86, (1H, bs, Im), 7.82 (2H, d, J = 2.0, 2 × Tp 3,5), 7.46 (1H, d, J = 2.0, Tp 3,5), 7.31 (1H, bs, Im), 7.18 (1H, ddd, J = 9.7, 4.8, 1.8, H3), 6.65 (1H, d, J = 10.2, H2), 6.6 (1H, buried, Im), 6.56 (1H, t, J = 2.0, Tp 4), 6.36 (1H, t, J = 2.0, Tp 4), 6.16 (1H, t, J = 2.0, Tp 4), 4.51 (1H, ddd, J = 7.5, 1.8, 1.8, H6), 4.05 (1H, ddd, J = 7.5, 1.6, 1.6, H5), 3.92 (3H, s, NCH_3), 3.58 (3H, s, $COOCH_3$), 3.55 (3H, s, 1-pos OCH_3), 3.56 (1H, b, H4), 2.4−2.2 (2H, m, H2′), 1.8−2.2 (2H, m, H1′) (BH not observed); **16B**, 8.26 (1H, d, J = 2.0, Tp 3,5), 8.11 (1H, d, J = 2.0, Tp 3,5), 8.09 (1H, d, J = 2.0, Tp 3,5), 8.03 (1H, bs, Im), 7.83 (1H, buried, Tp 3,5), 7.54 (1H, d, J = 2.0, Tp 3,5), 7.35 (1H, d, J = 2.0, Tp 3,5), 7.28 (1H, bs, Im), 6.99 (1H, ddd, J = 9.8, 4.8, 1.8, H3), 6.67 (1H, bs, Im), 6.59 (1H, t, J = 2.0, Tp 4), 6.51 (1H, buried, H2), 6.46 (1H, t, J = 2.0, Tp 4), 6.16 (1H, t, J = 2.0, Tp 4), 4.83 (1H, ddd, J = 7.7, 1.7, 1.6, H5), 3.91 (3H, s, NCH_3), 3.62 (3H, s, $COOCH_3$), 3.56 (1H, buried, H6), 3.33 (1H, m, H4), 3.06 (3H, s, OCH_3), 2.4−2.2 (2H, m, H2′), 1.8−2.2 (2H, m, H1′) (BH not observed). ^{13}C (acetone-d_6, ambient temperature, δ): **16A** (select resonances), 196.2 (CO), 187.7 (C1), 173.8 or 173.6 (*C*OOCH_3, other is **16B** *C*OOCH_3), 153.0 (C3), 68.7 (C5), 51.7 (CO*O*CH_3), 43.8 (C4). (**16B**) 195.1 (CO), 186.3 (C1), 173.8 or 173.6 (*C*OCH_3, other is **16A** *C*OCH_3), 151.8 (C3), 71.3 (C5), 51.7 (CO*C*H_3), 45.2 (C4). IR: $\nu_{C\equiv O}$ = 1853 cm^{-1} (vs), $\nu_{C=O}$ = 1728 cm^{-1} (s). CV: $E_{p,a}$ = 1.09 V, $E_{p,c}$ = −1.02 V. Anal. Calcd for $C_{26}H_{31}BF_3N_8O_7ReS$: C, 36.58; H, 3.66; N, 13.13. Found: C, 36.77; H, 3.66; N, 13.23.

Compounds 17−28 were synthesized from compounds 5−16 as follows: The anisolium complex (1.5 × 10^{-4} mol) was combined with $CuBr_2$ (1.8 × 10^{-4} mol) in a vial with a magnetic stir bar. Acetone (~5 mL) was added, and the reaction was stirred open to air for 30 min. The mixture was added dropwise to stirring hexanes (100 mL), and the resulting cloudy solution was stirred vigorously until clear. The supernatant was collected, filtered through a medium frit, and concentrated under reduced pressure to afford the crude product. The product was purified by preparatory thin-layer chromatography using hexanes/EtOAc as the eluent.

Compounds 17, 20, 22, 24, and 34 were synthesized from compounds 29−33 as follows: The anisolium complex (0.100 g) was combined with $CuBr_2$ (0.038 g) and sodium bicarbonate (0.030 g) in a vial with a magnetic stir bar. Acetonitrile (~4 mL) was added, and the reaction was stirred for 60 min. Volatiles were removed by rotary evaporation, and the remaining residue was taken up in chloroform and added to stirring hexanes (100 mL). The resulting mixture was filtered. Volatiles were removed from the filtrate by rotary evaporation, and the remaining colorless residue was purified by preparatory thin-layer chromatography using hexanes/EtOAc as the eluent.

Except where otherwise noted, compounds 29−33 were synthesized as follows: To a mixture of TpRe(CO)(BuIm)(5,6-η^2-anisole) (**4**, 0.100 g, 1.52 × 10^{-4} mol) and diphenylammonium triflate (0.100 g, 3.13 × 10^{-4} mol) at −40 °C was added a solution of a Michael acceptor (1.52 × 10^{-3} mol) in acetonitrile (0.5 g) at −40 °C. The resulting yellow mixture was stirred at −40 °C for ~48 h, during which time it became a deep red solution. Brine (5 mL) and benzene (5 mL) were then added, and the resulting mixture was shaken vigorously at ambient temperature. The top layer (dark brown, organic) was removed, and the remaining (aqueous) portion was extracted once more with benzene (1 mL). To the combined organic portions was added sodium sulfate (5 g), and the resulting mixture was stirred for 1 h. The solid portion was removed by filtration and rinsed with benzene (4 mL). The filtrate was added to stirring hexanes (100 mL) using a benzene (1 mL) rinse. The resulting mixture was stirred until the solution portion was completely transparent. The solution portion was then removed by decantation, and the remaining material was dissolved in methylene chloride (1 mL). To this solution was added benzene (4 mL), and the resulting solution was added to stirring hexanes to give a precipitate that was collected by filtration, rinsed with hexanes, and dried in vacuo to give a tan solid.

[TpRe(CO)(BuIm)(4*β*-(3-oxobutyl)-5α,6α-η^2-(4*H*-anisolium))](OTf) (29). MVK (3.17 × 10^{-4} mol) was used in the synthesis of this compound. It was isolated as a >20:1 mixture of **29A** and **29B** (89.2%). ^{1}H NMR (acetone-d_6, ambient temperature, δ): major diastereomer (**29A**), 8.13 (2H, d, J = 2.1, 2 × Tp 3,5), 7.99 (1H, d, J = 2.4, Tp 3,5), 7.83 (1H, d, J = 2.4, 2 × Tp 3,5), 7.82 (1H, very broad, Im), 7.41 (1H, d, J = 2.4, Tp 3,5), 7.40 (1H, t, J = 1.5, Im), 7.20 (1H, ddd, J = 9.9, 5.1, 2.1, H3), 6.64 (1H, very broad, Im), 6.63 (1H, ddd, J = 9.9, 1.5, 1.5, H2), 6.56 (1H, t, J = 2.4, Tp 4), 6.36 (1H, t, J = 2.4, Tp 4), 6.17 (1H, t, J = 2.4, Tp 4), 4.7 (1H, very broad, BH), 4.54 (1H, d, J = 7.8, H6), 4.22 (2H, t, J = 7.2, NCH_2), 4.10 (1H, d, J = 7.5, H5), 3.60 (3H, s, OCH_3), 3.53 (1H, m, H4), 2.51 (2H, m, H2′), 2.01 (3H, s, H4′), 1.92, (2H, m, H1′), 1.79 (2H, m, NCH_2CH_2), 1.26 (2H, m, CH_2-CH_3), 0.90 (3H, t, J = 7.5, CH_2CH_3); minor diastereomer (**29B**), 8.24 (1H, d, J = 2.1, Tp 3,5), 8.12 (1H, buried, Tp 3,5), 8.09 (1H, d, J = 2.7, Tp 3,5), 8.01 (1H, bs, Im), 7.54 (1H, d, J = 2.1, Tp 3,5), 7.36 (1H, bs, Im), 7.31 (1H, d, Tp 3,5), 6.99 (1H, ddd, J = 9.9, 5.1, 2.1, H3), 6.73 (1H, bs, Im), 6.59 (1H, t, J = 2.1, Tp 4), 6.48 (1H, buried, H2), 6.46 (1H, t, J = 2.4, Tp 4), 6.17 (1H, buried, Tp 4), 4.81 (1H, d, J = 7.5, H5), 3.59 (1H, buried, H6), 3.29 (1H, m, H4), 3.06 (3H, s, OCH_3), 2.51 (2H, buried, H2′), 2.01 (3H, buried H4′), 1.92 (2H, buried, H1′) (1 × Tp 3,5, BH, NCH_2, NCH_2CH_2, CH_2CH_3, and CH_2CH_3 buried or otherwise indiscernible). ^{13}C NMR (acetone-d_6, ambient temperature, δ): major diastereomer (**29A**), 207.6 (C3′), 196.1 (CO), 187.9 (C1), 153.6 (C3), 144.4 (Tp 3,5), 143.9 (Tp 3,5), 143.0 (Tp 3,5), 138.5 (Tp 3,5), 138.0 (Tp 3,5), 136.2 (Tp 3,5), 131.6 (Im), 123.9 (C2), 121.8 (Im), 121.0 (Im), 108.1 (Tp 4), 107.7 (2 × Tp 4), 69.2 (C5), 59.0 (OCH_3), 57.4 (C6), 48.5 (NCH_2), 44.0 (C4), 40.1 (C2′), 33.3 (NCH_2CH_2), 32.2 (C1′), 29.8 (buried, C4′), 20.0 (CH_2CH_3), 13.6 (CH_2CH_3). IR: $\nu_{C\equiv O}$ = 1852 cm^{-1} (vs), ν_{BH} = 2497 cm^{-1} (w), $\nu_{C=O}$ = 1710 cm^{-1} (s). CV: $E_{p,a}$ = 1.18 V (II/I), $E_{p,c}$ = −1.04 V. Anal. Calcd for $C_{29}H_{37}$-$BF_3N_8O_6ReS$: C, 39.59; H, 4.24; N, 12.74. Found: C, 39.43; H, 4.23; N, 12.72.

Conclusion

The {TpRe(CO)(RIm)(anisole) complexes **1**−**4** undergo Michael addition reactions with a variety of α,*β*-unsaturated carbonyl compounds under mild conditions to diastereoselectively afford anisolium products substituted exclusively at C4. The high degree of stereoselectivity observed in these reactions is attributed to the trapping of a single coordination diastereomer found in solid samples of TpRe(CO)(RIm)(arene) complexes and to a Diels−Alder-like transition state for the Michael reaction. Anisolium complexes **5**−**16** and **29**−**33** are surprisingly stable and resistant to rearomatization. They may be isolated and manipulated at 25 °C under an inert atmosphere without degradation. However, rearomatization and decomplexation may be accomplished by oxidation of the Re(I) center to afford net aromatic substitution products in moderate overall yields. When compared to the analogous pentaammineosmium(II) systems, the TpRe(CO)(RIm)(anisole) complexes show dramatically increased reactivity, undergoing Michael addition reactions under mild conditions with greater stereocontrol at the benzylic position. While the present system is not suitable

for controlling the absolute stereochemistry of the Michael addition products, this study demonstrates how the solid state[30,45] can impact the stereochemistry of organic transformations with η^2-coordinated arenes.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the ACS, for partial support of this research (ACS-PRF#36638-AC1). This work was also supported by the NSF (CHE0111558 and 9974875) and the NIH (NIGMS: R01-GM49236).

(45) Smith, P. L. Ph.D. Dissertation; University of Virginia, Charlottesville, VA, 2002, pp 160−161.

Supporting Information Available: Synthetic procedures and detailed characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

JA047054J