Table I. Stereoselection of Cycloadditions of C-5 Substituted Cyclopentadienes

entry	compd	X	reaction time[a]	addition ratio anti	addition ratio syn
a	1	SH	3 h	4.5[b]	5.5[b]
b	2	SMe	27.5 h	9	1
c	2	SMe	46 h	11.5[b]	1[b]
d	3	SOMe	48 h	10	0
e	4	SO_2Me	9 days	10	0
f	5	OH	<30 s	0	10
g	6	OMe	<10 min	0	10
h	7	NHAc	3.5 h	0	10
i	7	NHAc	3.5 h	trace	10[b]
j	8	NH_2	3.5 h	0	10[b]
k	9	H	<30 s	2[13]	8[13]

[a] Approximate time for diene disappearance (TLC); reactions were run at 22 °C; yields in all cases were >90%; ratios were determined by integration of ^1H NMR spectra of the total reaction mixture. [b] *N*-phenylmaleimide adduct.

initio calculations[25] suggest that the electron density is decreased on the diene syn face and that the sulfur lone pair electrons interact more strongly with the diene (HOMO) than in the case of oxygen. This interaction must be disrupted prior to cycloaddition and favors the anti approach. The relative rates and stereoselection are also influenced by substituent orientation. The distal oxygen conformer is the most reactive and leads rapidly to adduct compared to the sulfur series in which both conformers have comparable energy. These factors—lone-pair interactions, conformational reactivity, and substituent electronegativity enhance anti cycloaddition in the sulfur series.

In conclusion, this study adds to our understanding of the facial preferences of addends in [4 + 2] cycloadditions of cyclopentadienes. Heteroatom-directed control of π-facial selectivity by variation of the substituent or through the judicious choice of mixed acetals (oxathiolane ketals) has considerable potential for the total synthesis of natural products. Approaches to multicyclic systems that utilize these features are under investigation.

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Supplementary Material Available: Synthetic schemes and brief reaction conditions for preparation of the dienes and adduct interconversions (2 pages). Ordering information is given on any current masthead page.

(23) Professor Franck has kindly informed us that acetylene dicarboxylates, tetracyanoethylene, and *N*-phenyltriazolinedione exhibit reversed facial selectivity in his acyclic dienes as also observed in an amino case by Kozikowski and co-workers[3] (also: Franck, R. W.; Tripathy, R.; Onan, K. D. *J. Am. Chem. Soc.* **1987**, in press and ref 16). Thus the thiomethyldiene **2** was treated with tetracyanoethylene. A single anti adduct was obtained whose structure was established by X-ray analysis. It seems likely that in acyclic cases more reactive dienophiles afford predominantly the anti (to the oxygen and nitrogen substituent) product as a consequence of the preferential trapping of a different rotamer ratio compared to maleic anhydride. This should allow a level of facial control by variation of the dienophile. In addition, recent evidence has indicated that cyanoethylene and triazolinediones react by an aziridinium imide (1,4-zwitterion) mechanism.[24]

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Molecular Recognition of Amino Acids: Two-Point Fixation of Amino Acids with Bifunctional Metalloporphyrin Receptors [1]

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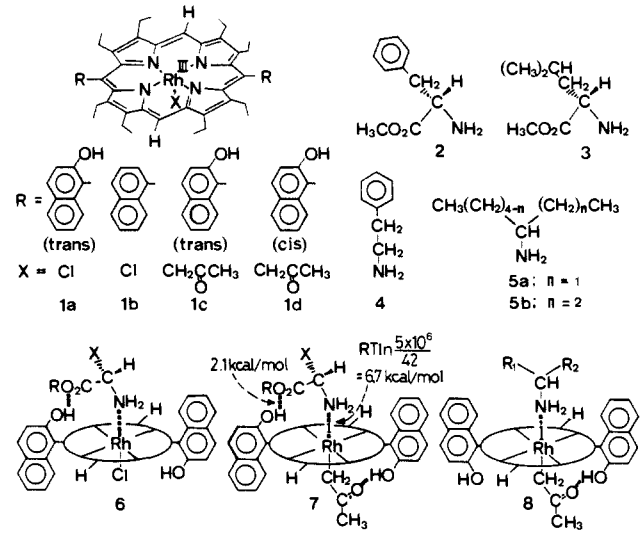
Amino acids can be solubilized in organic solvents in the form of ammonium or carboxylate ion upon formation of crown complexes[2] or hydrophobic salts.[3] The complexation of zwitterionic forms is generally weak,[4] but some elaborate receptor systems for these have been reported.[5,6] Nonionic *amino acids* ($H_2NCHRCO_2H$), on the other hand, seem to be a potential form in apolar organic solutions but have been receiving surprisingly little attention.[7] We report here the first successful two-point fixation of amino acids and amino esters in *nonionic forms* via simultaneous metal-coordination and hydrogen-bonding interactions with bifunctional metalloporphyrin receptors.



Chlororhodium(III) complexes of *trans*-5,15-bis(2-hydroxy-1-naphthyl- (**1a**) and 5,15-bis(1-naphthyl)octaethylporphyrin (**1b**)[8] form stable 1:1 rhodium–amine adducts, in a practically irreversible manner,[9] with L-phenylalanine methyl ester (**2**) and L-leucine methyl ester (**3**) as well as 2-phenylethylamine (**4**) and 3- (**5a**) or 4-aminoheptane (**5b**) as references in $CHCl_3$.[10] The

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(9) All the adducts can be isolated by chromatography. Addition of a large excess amount of the second amine to a $CHCl_3$ solution of a preformed amine adduct led to no amine exchange. Amine adduct **1a–2** underwent no decomplexation when its $CHCl_3$ solution was stirred with 6 N aqueous HCl for 24 h.

(10) For the amine coordination to Rh(III) porphyrin, see: (a) Kadish, K. M.; Yao, C.-L.; Anderson, J. E.; Cocolios, P. *Inorg. Chem.* **1985**, *14*, 4515. (b) Anderson, J. E.; Yao, C.-L.; Kadish, K. M. *J. Am. Chem. Soc.* **1987**, *109*, 1106.

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Table I. Binding Constants of Amines with Rhodium(III) Porphyrins in $CHCl_3$ at 15 °C[a]

amine	K (M^{-1}) Rh porphyrin 1c	K (M^{-1}) Rh porphyrin 1d
3	5×10^6	1.6×10^5
5b	2.9×10^5	3.9×10^5

[a] $[\text{Rh porphyrin}]_{total} = 4.30 \times 10^{-5}$ M.

^1H NMR and IR spectra of adduct **1a–2** for $CDCl_3$ or $CHCl_3$ solutions showed nonequivalent OH proton resonances at δ 8.85 (1 H) and 6.00 (1 H) and ν_{OH} and ν_{CO} at 3430 and 1728 cm^{-1}, respectively. A large (~3 ppm) downfield shift of one OH proton and significant shifts to lower wavenumbers in ν_{OH} (~100 cm^{-1}) and ν_{CO} (14 cm^{-1}) as compared with those for reference compounds[11] indicate that the adducts of **1a** and amino esters contain an intramolecular hydrogen bond between OH and CO_2CH_3 groups in addition to a common Rh–NH_2– coordination bond (refer to **6**, R = CH_3 and X = $CH_2C_6H_5$ or $CH_2CH(CH_3)_2$).[12] A similar dual interaction has been observed for the C-bound acetone–rhodium derivatives of *trans*-bis(hydroxynaphthyl)-porphyrin (**1c**) and its cis isomer (**1d**).[8] Compound **1a** in $CDCl_3$ was also found to extract 1 mol of free amino acids such as phenylalanine and leucine in water at neutral pH to form similar two-point amino *acid* adducts (**6**, R = H and X = $CH_2C_6H_5$ or $CH_2CH(CH_3)_2$) irreversibly; ν_{OH} centered at 3400 cm^{-1} and ν_{CO} 1717 cm^{-1} for the phenylalanine adduct.[13]

Reversible amine coordination (eq 1) was achieved by using related Rh(III) porphyrins having an organic trans ligand in place of Cl. Amines **2–5** reversibly bind with **1c** and **1d**. In the latter

$$\text{Rh(III)} + \text{amine} \underset{}{\overset{K}{\rightleftharpoons}} \text{rhodium(III)–amine} \qquad (1)$$

the acetone moiety is attached to Rh at the OH-containing side of the porphyrin plane.[8] The binding constants (K) for **3** and **5b** were determined by spectrophotometric titration with good isosbestic behaviors[14] and are summarized in Table I. Although **1d** whose open coordination site has no nearby OH groups (refer to **8**) shows a slight preference for **5b** over **3** ($K_{1d}(3)/K_{1d}(5b)$ = 0.41), **1c** binds **3** 17 times more strongly than **5b** ($K_{1c}(3)/K_{1c}(5b)$ = 17). Although, in a different viewpoint, **5b** is bound with **1d** slightly more tightly than with **1c** ($K_{1c}(5b)/K_{1d}(5b)$ = 0.74), **3** prefers **1c** to **1d** by a factor of 31 ($K_{1c}(3)/K_{1d}(3)$ = 31). These results indicate that the hydrogen bonding in the adduct **1c–3**[15] (**7**, R = CH_3 and X = $CH_2CH(CH_3)_2$) gives rise to a selectivity factor of 17/0.41 = 31/0.74 = 42, corresponding to a stabilization energy of RT ln 42 = 2.1 kcal/mol (15 °C). Reversible and highly selective amino ester binding with **1c** was directly shown by the NMR spectrum for a 1:2:2 mixture of **1c**, **3**, and **5b** in $CDCl_3$ ([**1c**] = 4.1 mM) affording two adducts **1c–3** and **1c–5b** in a ratio of approximately 20:1.[16] Reversible amino acid extraction from neutral aqueous solutions was also achieved with **1c** but practically not with **1d** which lacks appropriate hydroxyl groups to assist ligand binding. Thus, vigorous stirring of a $CDCl_3$ solution of **1c** (4.1 mM) and a saturated aqueous solution of phenylalanine gave adduct **7** (R = H and X = $CH_2C_6H_5$)[17] (ν_{CO} for the CO_2H group at 1720 cm^{-1})[13] together with unbound **1c** in a ratio of 1:2.4. Other amino acids such as tryptophan, leucine, and isoleucine were extracted similarly. Competitive extraction of phenylalanine and leucine demonstrated no significant difference in their extractabilities, indicating that π stacking interactions[6] between an aromatic amino acid and the porphyrin plane are not important.

This work presents a novel example of two-point fixation of amino acids and amino esters in nonionic forms. It is significant that the weaker interaction, hydrogen bonding, in fact brings about a sizable selectivity for amino esters in homogeneous solutions and also plays a crucial role in amino acid extraction from neutral aqueous solutions. Suitable modification of the present porphyrin may allow three-point interactions[18] with amino acids. Trifunctional chiral metalloporphyrins have been prepared,[19] and further work is now under way along this line.

Acknowledgment. This work was supported by Grant-in-Aid from the Ministry of Education, Science, and Culture of Japan.

(11) The corresponding absorptions for reference compounds are as follows: δ_{OH}, 6.15 (1 H) and 5.68 (1 H) for adduct **1a–4** and 5.23 (2 H) for the free base porphyrin of **1a**; ν_{OH}, 3529 cm^{-1} for **1a–4**, 3524 cm^{-1} for **1a**, and 3520 cm^{-1} for the free base porphyrin of **1a**; ν_{CO}, 1742 cm^{-1} for **1b–2**.

(12) Other characteristic NMR signals for **1a–2** are as follows: δ −4.42 and −5.23 (both 1 H, m, diastereotopic NH_2), −3.20 (1 H, m, $CHNH_2$), 0.07 and 0.48 (both 1 H, m, diastereotopic $CH_2C_6H_5$), and 10.28 and 10.20 (both 1 H, s, meso-H).

(13) A shift to lower wavenumber by ~20 cm^{-1} in ν_{CO} as compared with ν_{CO} at 1737 cm^{-1} for adduct **1b**–phenylalanine is consistent with an intramolecular hydrogen bonding between OH and CO_2H groups in **6** (R = H) and **7** (R = H).

(14) Compounds **1c** and **1d** undergo a considerable red-shift of their Soret absorption upon complex formation with amines; e.g., λ_{max} for **1c–3** (**7**, R = CH_3 and X = $CH_2CH(CH_3)_2$) ($CHCl_3$ solution) 421, 537, and 567 nm. Spectra in the region of 500–600 nm with varying amounts of amine were recorded, where isosbestic points were observed at 528, 548, and 566 nm in the case of titration of **1c** with **3**. Binding constants (K) were calculated from absorbance changes at 557 nm, a λ_{max} for **1c**, according to K = [rhodium–amine]/[Rh][amine].

(15) Adduct **1c–3** (**7**) and **1d–3** (refer to **8**) showed ν_{CO} for CO_2CH_3 groups respectively at 1728 and 1740 cm^{-1}, indicating a characteristic shift by 12 cm^{-1} in ν_{CO} for **1c–3** due to hydrogen bonding.

(16) Adducts **1c–3** and **1c–5b** gave sharp NMR resonances in high field region at −30 °C: δ −5.26 and −5.60 (diastereotopic CH_3COCH_2-Rh), −4.69 and −5.50 (NH_2), −3.10 ($CHNH_2$), −2.10 (CH_3COCH_2-Rh), −1.23 ($CH_2CH(CH_3)_2$), −0.71 ($CH(CH_3)_2$), and −0.14 and −0.91 ($CH(CH_3)_2$) for **1c–3**; δ −5.74 (NH_2), −5.32 (CH_3COCH_2-Rh), −3.88 ($CHNH_2$), −2.10 (CH_3COCH_2-Rh), and −2.60, −1.40, −1.15, −0.96, and −0.10 (CH_2 and CH_3 in amine ligand) for **1c–5b**. The selectivity (**1c–3**)/(**1c–5b**) is based on integration of these high field signals in the spectrum for a 1:2:2 mixture of **1c**, **3**, and **5b** at −30 °C.

(17) Adduct **7** (R = H and X = $CH_2C_6H_5$) in the presence of unbound **1c** gave sharp and characteristic NMR signals at −30 °C for the phenylalanine and acetone ligands and meso protons in a similar manner as adduct **1c–3** (**7**),[16] but *both* hydroxyl (in the naphthol moiety) and carboxyl proton resonances could not be detected. This was also the case for adduct **6** (R = H and X = $CH_2C_6H_5$). It seems that the protons in the OH and CO_2H groups which are hydrogen bonded undergo extensive broadening due to rapid exchange.

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The C=C Double Bond of Tetrafluoroethylene

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Tetrafluoroethylene is an unusual olefin, with one of the weakest carbon–carbon double bonds known [D(C=C) ~ 60 kcal/mol]. Unfortunately, the experimental C=C bond energy for C_2F_4 remains quite uncertain, with values ranging from 53 to 76 kcal/mol.[1-3] In addition, the nature of the double bond in C_2F_4 has also been disputed: the importance of bent or "banana" bonds versus the conventional σ and π bonds has not been addressed quantitatively, although a recent paper has suggested that bent

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(1) An indirect determination of $D(F_2C{=}CF_2)$ from the heat of formation of C_2F_4 ($\Delta H°_{f,298}$ = −157.4 ± 0.7 kcal/mol) and a 1977 experimental value for $\Delta H°_{f,298}(CF_2)$ = −52. kcal/mol (Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695) yields D_{298} = 53.4 ± 0.7 kcal/mol.

(2) Using another (more recent) determination of $\Delta H°_{f,298}(CF_2)$ = −44.2 ± 1 kcal/mol (Berman, D.; Bomse, D. S.; Beauchamp, J. L. *Int. J. Mass Spec. Ion Phys.* **1981**, *39*, 263) yields D_{298} = 69.0 ± 2.7 kcal/mol.

(3) This value constitutes the only directly determined bond energy (D_{298} = 76.3 ± 3 kcal/mol) for C_2F_4 in a Knudsen cell equilibrium study at high temperature (~1200 K) by Zmbov et al. (Zmbov, K. F.; Uy, O. M.; Margrave, J. L. *J. Am. Chem. Soc.* **1968**, *90*, 5090).

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