Table I

polymer	yield, %[a] 10:1[c]	yield, %[a] 5:1[c]	ee of L isomer, %[b] 10:1[c]	ee of L isomer, %[b] 5:1[c]
poly(A)	6	3	58	52
poly(I)	7	5	53	57
poly(U)	7	5	48	45
poly(C)	2	1	41	35

[a] Yields are reported as the percentage of mononucleotide units acylated by the imidazolide of *N*-(3,5-dinitrobenzoyl)-DL-alanine. [b] The enantiomeric excess (ee) of the polymer-bound *N*-(3,5-dinitrobenzoyl)alanine is defined as the % *L* isomer minus the % *D* isomer. Uncertainties are ±3%. [c] The ratio of reactants, (imidazolide):(nucleotide units).

dient.[5] The amino acid derivative was detected by its absorbance at 254 nm, and the acylation yield was determined from the chromatographic peak area using a molar absorptivity (254 nm) of 14.6×10^3 M^{-1} cm^{-1} (measured in 0.1 M NH_4OAc, pH 4.7, containing 20% acetonitrile). The enantiomers of the purified dinitrobenzoylalanine were separated by HPLC on a chiral stationary phase consisting of one enantiomer of 1-amino-1-(6,7-dimethylnaphth-1-yl)-2-methylpropane linked to a 5-μm silica matrix.[6] The derivatives were eluted with a mobile phase of 4:1 water/methanol containing 1 g/L $KHCO_3$ and 20 g/L K_2SO_4 and were detected by their absorbance at 254 nm. Relative amounts of the D and L enantiomers were determined from the chromatographic peak areas. Table I shows the percent of nucleoside hydroxyl groups that were acylated and the ee of the L isomer that was incorporated into each polymer. The reactant *N*-(3,5-dinitrobenzoyl)-DL-alanine was shown to be racemic (ee = 0 ± 3%) by HPLC on the chiral stationary phase.

Previously, polynucleotides have been acylated by the imidazolides of *N*-acetyl-L-amino acids and L-amino acid trifluoroacetates,[7-9] but in these experiments, no attempt was made to compare the behavior of D- and L-amino acid derivatives. We recently reported that aminoacylation of the "internal" 2′-hydroxyl group of a dinucleoside monophosphate (D-inosinylyl-D-inosine) by the imidazolide of racemic *N*-(*tert*-butoxycarbonyl)alanine resulted in the formation of excess L ester.[2] Since aminoacyl imidazoles are believed to acylate polyribonucleotides principally at the 2′-hydroxyl groups along the ribose backbone,[8,9] the preferential incorporation of (dinitrobenzoyl)-L-alanine into the polymers is consistent with the earlier work. The stereoselectivity appears to be somewhat lower for the pyrimidine polymers than for the purine polymers, possibly reflecting the smaller amount of secondary structure in the former. The overall yields of esters (Table I) were consistent with the reported relative rates of polymer acylation by *N*-acetylamino acid imidazolides, which decreased in the order poly(U) > poly(A) > poly(C).[7-9] Stereoselective diastereomer formation by amino acids has been reported previously,[10-14] but there appears to be no prior case involving the aminoacylation of a nucleic acid.

Derivatives of amino acids have been shown to interact stereoselectively with polynucleotides. Gabbay et al.[15] found that *N*-(L-aminoacyl)diaminoethanes stabilized RNA double helices to a greater extent than did the D-amino acid derivatives, while the D isomers afforded single-stranded polymers greater protection against hydrolysis by ribonucleases.[16] Similarly, L-lysyl-L-amino acid dipeptides stabilized double-helical complexes more than did the corresponding L-lysyl-D-amino acid diastereomers.[15] These noncovalent interactions appeared to depend upon the presence of a diammonium salt, since there was little discrimination when the nucleic acid interacted with the D- or L-amino acid alone.

Some details of the reaction reported here argue against its direct involvement in the early evolution of the chirality of nucleosides and amino acids. In particular, the presence of a N-protecting group precludes its participation in a recursive mechanism for peptide-bond formation. Moreover, we have observed that when the activated amino acid carries no N-protecting group, the selectivity is reversed, and it is the D-amino acid that is selected by D polynucleotides.[2,17] The structural features responsible for these stereochemical results are now under investigation.

Acknowledgment. We thank Professor W. H. Pirkle for the gift of a chiral HPLC column and the National Aeronautics and Space Administration (Grant NAGW-493) for financial support.

Registry No. Poly(A), 24937-83-5; poly(I), 30918-54-8; poly(U), 27416-86-0; poly(C), 30811-80-4; imidazolide of *N*-(3,5-dinitrobenzoyl)-DL-alanine, 91157-76-5.

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(17) Usher, D. A.; Profy, A. T.; Needels, M. C., unpublished results.

Very High 1,2-Asymmetric Induction in the Reaction of Allyl-9-BBN with Certain Imines. Evidence for a Stereoelectronic Effect To Enhance the Cram Selectivity

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Received April 18, 1984

The discovery of new methods for 1,2- and 1,3-asymmetric induction in acyclic systems has been of keen interest in synthetic and theoretical organic chemistry.[1] Especially, the Cram/anti-Cram problem has been one of the longstanding concerns, and unfortunately the Cram selectivity of ordinary aldehydes having an α-chiral center is generally no so high (eq 1).[2-4] We have discovered that the Cram selectivity is remarkably enhanced in the reaction of imines with allyl-9-BBN (eq 2). This finding and elucidation of the enhancement provide a conceptual advance in the Cram/anti-Cram problem.

The low Cram selectivity in the reaction of allyllic organo-

(1) For example: Heathcock, C. H. In "Comprehensive Carbanion Chemistry"; Durst, T., Buncel, E., Eds.; Elsevier: New York, 1984. Evans, D. A.; Nelson, J. V.; Taber, T. R. "Topics in Stereochemistry"; Wiley-Interscience: New York, 1982; Vol 13, p 1. "Asymmetric Synthesis"; Morrison, J. D., Ed.; Academic Press: New York, 1983; Vol 2. Masamune, S. In "Organic Syntheses Today and Tomorrow"; Trost, B. M., Hutchinson, R., Eds.; Pergamon Press: New York, 1981; p 197. Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 555. Yamamoto, Y.; Maruyama, K. *Heterocycles* **1982**, *18*, 357.
(2) Excellent 1,2- and 1,3-asymmetric induction through chelation control has been realized in the nucleophilic addition of organometallics to α- and β-alkoxy substituted aldehydes. Reetz, M. T.; Kesseler, K.; Schmidtberger, S.; Wenderoth, B.; Steinbach, R. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 989. Reetz, M. T.; Jung, A. *J. Am. Chem. Soc.* **1983**, *105*, 4833. Still, W. C.; Schneider, J. A. *Tetrahedron Lett.* **1980**, *21*, 1035. Still, W. C.; McDonald, J. H. *Ibid.* **1980**, *21*, 1031.

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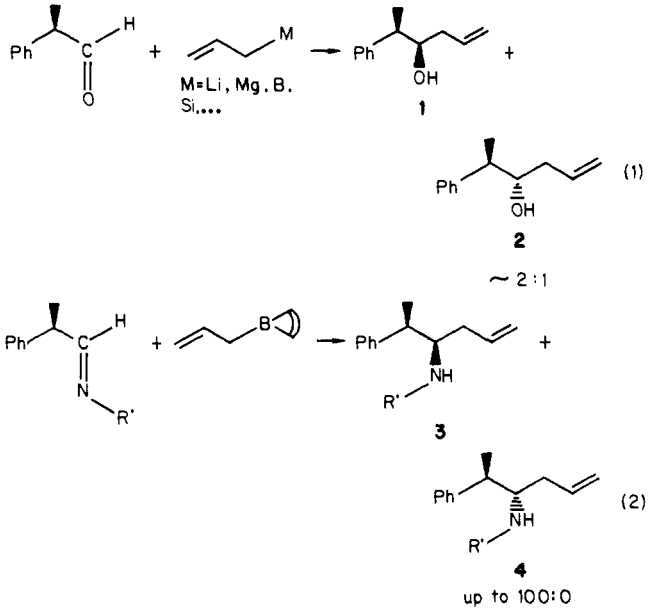
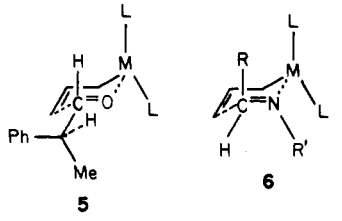


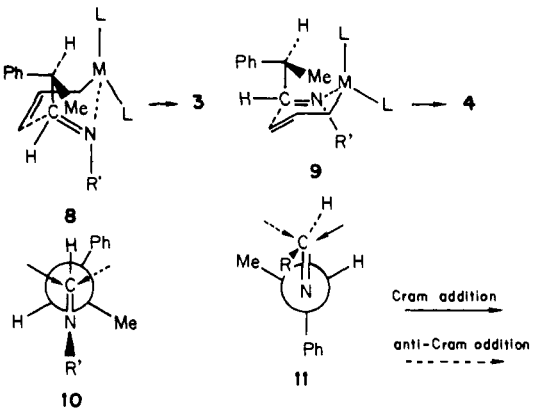
metallic compounds with ordinary chiral aldehydes having no ability to be chelated is presumably due to the fact that the selectivity is determined only by the conventional steric factor at the chiral center. Since the α-chiral center goes to the equatorial position of **5**, the steric influence of ligand (L) does not reach the



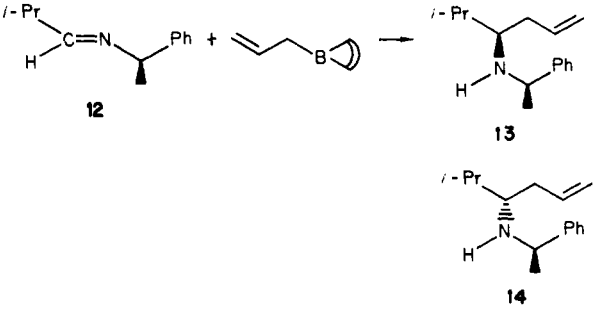
chiral center. If the chiral center goes to the axial position, the selectivity must depend upon both the original steric factor of the chiral center and the steric influence of L. We have disclosed that the reaction of imines with allylic organometallic compounds proceeds through such a transition state (**6**), presumably due to the stereoelectronic effect of the imine group.[5] Therefore, we examined the reaction of imines having α-chiral centers with allylic organometallics. The results are summarized in Table I.

Even allylmagnesium chloride produced fairly good Cram selectivity in the imine reaction (entry 3 vs. 6). Allyl-9-BBN gave the Cram product[6] either exclusively or very predominantly (entries 1 and 2). This remarkable enhancement may be explained as follows. The conformation of the chiral center is fixed as shown in **8** owing to the steric influence of L, and the allyl group attacks from the less hindered side (**8** and **10**). The transition state, **9**, is highly destabilized owing to the steric repulsion between the methyl group and the 9-BBN ring protons.[9]

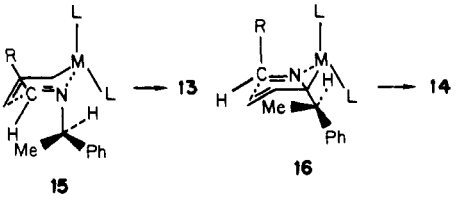
The steric interaction between R group and L (**6**) is a sort of 1,3-diaxial interaction. A similar interaction between the R′ group



and L may be conceivable, though it is a sort of 1,2-axial–equatorial interaction. Therefore, we examined the reaction of **12** with allyl-9-BBN. The Cram product (**13**) was obtained very



predominantly; **13**:**14** = 92:8 (eq 3).[10] Here again, the conformation of the chiral center is probably fixed as shown in **15**. The



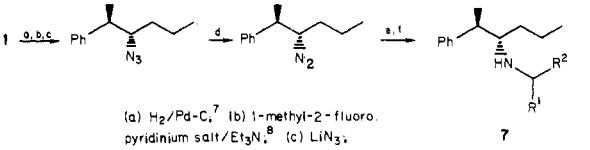
allyl group attacks from the less hindered side (**11** and **15**). The transition state (**16**) is destabilized due to the steric repulsion between the methyl group (and/or phenyl group) and L.[11] Normally, the 1,3-diaxial interaction is more stronger than the 1,2-axial–equatorial interaction. Accordingly, the selectivity of entry 2 is 100%, while that of **12** is 92%.[12]

(3) Midland has reported that the reduction of α-phenylpropionaldehyde with LiBH(*sec*-Bu)$_3$ proceeds with an exceptionally high Cram selectivity. Midland, M. M.; Kwon, Y. C. *J. Am. Chem. Soc.* **1983**, *105*, 3725.

(4) Heathcock has found an excellent Cram selectivity in the Lewis acid mediated reaction of silyl ketene acetals with ordinary aldehydes. Heathcock, C. H.; Flippin, L. A. *J. Am. Chem. Soc.* **1983**, *105*, 1667.

(5) Yamamoto, Y.; Komatsu, T.; Maruyama, K., paper presented at the Fifth International Symposium on Boron Chemistry, Swansea, Wales, July 1983, and at the Eighth International Symposium on Synthesis in Organic Chemistry, Cambridge, England, July 1983. The manuscript will be submitted shortly. The reaction of crotyl-9-BBN with certain imines provides the erythro homoallylamines predominantly, excluding the possibility of a boat transition state. The coordination of boron to the nitrogen is essential to induce the reaction, which indicates no participation of an open transition state.

(6) The structure was determined as follows. The Cram product **1** was converted into the anti-Cram amine **7**. Similarly, the anti-Cram isomer **2**



was transformed into the Cram amine. The reduction products of the homoallylamines were compared with authentic samples thus obtained.

(7) The double bond must be reduced prior to the displacement with N_3^-. The direct reaction of **1** was accompanied with significant amounts of the β-elimination product.

(8) Hojo, K.; Kobayashi, S.; Soai, K.; Ikeda, S.; Mukaiyama, T. *Chem. Lett.* **1977**, 635.

(9) The bridgehead proton ("H") of 9-BBN ring covers the six-membered ring. The plane of the C–R bond of imine groups and the plane of the C–"H" bond intersects with nearly orthogonal angle. See also: Yamamoto, Y.; Yatagai, H.; Maruyama, K. *J. Am. Chem. Soc.* **1981**, *103*, 3229.

(10) The structure of **13** and **14** was determined as described in ref 6. (4*S*)-5-Methyl-4-hexanol, prepared by the literature procedure (Hoffmann, R. W.; Herold, T. *Chem. Ber.* **1981**, *114*, 375), was converted into (4*R*)-5-methyl-4-hexylamine. Reduction of **13** with $Pd(OH)_2$ on carbon gave the corresponding (4*R*)-5-methyl-4-hexylamine.

Table I. High Cram Selectivity of Imine Reactions[a]

entry	imine, RCH=NR′ R	R′	allylorganometal M	Cram (3): anti-Cram (4)
1	$PhCH(CH_3)$	*n*-Pr	9-BBN	96:4
2	$PhCH(CH_3)$	*i*-Pr	9-BBN	100:0
3	$PhCH(CH_3)$	*n*-Pr	MgCl	84:16
4	$PhCH(CH_3)$	*i*-Pr	MgCl	70:30
entry	aldehyde		allylorganometal	Cram (1): anti-Cram (2)
5	$PhCH(CH_3)CHO$		9-BBN	55:45
6			MgCl	60:40
7			$SiMe_3$[b]	70:30

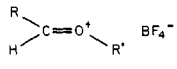
[a] All reactions were carried out on a 1-mmol scale at −78 °C under N_2 and quenched at 0 °C. Total isolated yields were in a range of 88–98%. The Cram:anti-Cram ratio was determined by ^1H NMR analysis and/or GLPC (THEED, 10%, 2 m). [b] $TiCl_4$ was useed as a Lewis acid.

The present findings suggest that the Cram/anti-Cram problem of carbonyl groups might be solved by a similar approach.[13] Further work along this line is now under active investigation.

(11) There may be a question that the bad interactions depicted in **9** and **16** can be avoided by rotating the carbon so that the hydrogen is in the position of the methyl in **9** and the phenyl in **16**. Inspection with a Dreiding model clearly indicates that such conformations are destabilized by the steric repulsion between the 9-BBN ring and the phenyl group in **9** and between the 9-BBN ring and the methyl group in **16**.

(12) (a) For addition of allylboronates to Schiff bases, see: Hoffmann, R. W.; Eichler, G.; Endesfelder, A. *Liebigs Ann. Chem.* **1983**, 2000. (b) When alkylorganometallics, such as $BuCu{\cdot}BF_3$ and $Bu_2CuLi{\cdot}BF_3$, were utilized, the Cram/anti-Cram selectivity was low (~4:1). This is reasonable since the six-membered cyclic transition state is not involved in this reaction. For the reaction of imines with $RCu{\cdot}BF_3$, see: Wada, M.; Sakurai, Y.; Akiba, K. *Tetrahedron Lett.* **1984**, *25*, 1079.

(13) An oxonium salt of aldehydes may take a trans geometry (**17**). If



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so, the R group may go to the axial position as described above. In fact, the reaction of α-phenylpropionaldehyde with allyl-9-BBN in the presence of $Et_3O^+BF_4^-$ produced **1** and **2** in a ratio of 7:3 (cv. entry 5). We are also investigating the Lewis acid mediated reaction of acetals bearing an α-chiral center, the results of which will be published soon.

Catalytic Reduction of CO_2 at Carbon Electrodes Modified with Cobalt Phthalocyanine

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Received April 20, 1984

We report the electrocatalytic reduction of aqueous solutions of $CO_2(g)$ to CO(g). The reaction occurs on carbon electrodes modified by adsorption of cobalt phthalocyanine, Co(Pc). The CO_2 reduction can be achieved within 300 mV of the thermodynamic CO_2/CO redox potential, and essentially the only carbon-containing product is CO(g). In contrast, Co(Pc) dissolved in homogeneous solution yields poor stability and low catalytic efficiency for CO_2 activation. Thus, in addition to an energy-efficient activation of $CO_2(g)$, this system demonstrates the effectiveness of chemical modification of electrodes in suppressing deleterious decomposition pathways during electrocatalysis.

The abundance of CO_2 as a one-carbon precursor has evoked considerable interest in its catalytic transformations.[1] Direct electrochemical reduction of CO_2 proceeds with large overpotentials[2] and generally yields formate. Electrocatalytic reductions of CO_2 to yield formate have been observed with supported Pd, as well as through the coupling of formate dehydrogenase with methylviologen.[3] Our efforts have focussed upon utilizing transition-metal complexes to promote reduction of CO_2 to CO via (1).

$$CO_2(g) + 2e^- + 2H^+(aq) \rightarrow CO(g) + H_2O(l) \quad (1)$$

Co(Pc)[4] was deposited onto pyrolytic graphite or carbon cloth surfaces either by adsorption from THF/Co(Pc) solutions or by droplet evaporation of THF/Co(Pc) solutions. Controlled potential electrolysis of such modified carbon cloth electrodes at −1.0 V vs. SSCE in aqueous solution (pH 5.0, 0.05 M citrate buffer, $E°'(CO_2/CO) = -0.65$ V vs. SCE[5]) under 1 atm of $CO_2(g)$ produced CO(g) as the major carbon-containing species. The catalytic nature of the reaction has been confirmed by formation of over 10^5 molar equiv of CO per molar equiv of electroactive catalyst (Table I).

Typical coulometric experiments (Table I) for potentials from −0.95 to −1.2 V vs. SCE indicate that 55–60% of the charge passed can be accounted for as CO formation and 35–30% detected as H_2, implying overall coulometric efficiencies of 90–95% for the catalytic reaction of Co(Pc) with CO_2/H_2O solutions. Although spot tests indicate the presence of oxalate and formate, as previously reported for a similar Co(Pc)/graphite system at more cathodic operating potentials,[6] we observe that these species are present in only trace amounts, and that the major carbon-containing product is gaseous CO.

Neither of the first two reported reduction potentials for Co(Pc) in DMF solution,[7] −0.40 and −1.40 V vs. SCE, correspond with the potentials at which we detect the onset of CO(g) production in aqueous media (−0.9 V vs. SCE). Furthermore, cyclic voltammograms for the $Co(Pc)^{0/-}$ couple are found to be identical under 1 atm of CO_2 or 1 atm of Ar for THF/Co(Pc) solutions as well as for C/Co(Pc) surfaces in aqueous media. This evidence seems to preclude initial binding of CO_2 to $Co(Pc)^-$ as a viable pathway unless there is only an extremely weak $Co(Pc)–CO_2$ interaction.

The aqueous reduction of Co(Pc)/graphite surfaces in the absence of CO_2 yields two proton-coupled reductions which appear at −0.58 and −0.95 V vs. SCE at pH 5.0. Over a range of pH 1.5–5.5 we observe a positive shift of E°′ for the first reduction wave of 59 mV/pH unit. The second reduction wave is quasi-reversible, and scan rates of 5 V/s yield reversible behavior for this couple. Interestingly, association of the first electrochemical wave with the one-electron $Co(Pc)^{0/-}$ couple implies that the

(1) (a) Eisenberg, R.; Hendricksen, D. E. *Adv. Catal.* **1979**, *28*, 79–172. (b) Kolomnikov, I. S.; Grigoryan, M. Kh. *Russ. Chem. Rev. (Engl. Transl.)* **1978**, *47*, 334–353. (c) Denise, B.; Sneeden, R. P. A. *CHEMTECH* **1982**, *12*, 108–112. (d) Darensbourg, D. J.; Kudaroshi, R. A. *Adv. Organomet. Chem.* **1983**, *22*, 129–168.

(2) (a) Russell, P. G.; Kovac, N.; Srinivasan, S.; Steinberg, M. *J. Electrochem. Soc.* **1977**, *124*, 1329–1338 and references cited therein. (b) Eggins, B. R.; McNeill, J. *J. Electroanal. Chem.* **1983**, *148*, 17–24. (c) Canfield, D.; Frese, K. W., Jr. *J. Electrochem. Soc.* **1983**, *130*, 1772–1773.

(3) (a) Stadler, C. J.; Chao, S.; Summers, D. P.; Wrighton, M. S. *J. Am. Chem. Soc.* **1983**, *105*, 6318–6320. (b) *Ibid.* **1984**, *106*, 2723–2725. (c) Stadler, C. J.; Chao, S.; Wrighton, M. S. *Ibid.*, **1984**, *106*, 3673–3675. (d) Parkinson, B. A.; Weaver, P. *Nature (London)*, in press.

(4) Co(Pc) was obtained from Eastman Kodak Co. and was purified by sublimation. $CO_2(g)$ concentrations were monitored with an Orion Model 95-02 electrode; CO(g) and $H_2(g)$ analyses were performed using a Carle Model 197-B gas chromatograph in the standard factory configuration (columns and thermistor at 60 °C, hydrogen-transfer catalyst at 570 °C; retention times, H_2, 1.5 min, CO, 10.7 min). Oxalate and formate were detected using standard qualitative spot test reagents,[6a] and quantitative determination of oxalate was performed polarographically by determination of Eu^{3+}. Cyclic voltammetric data (100–500 mV/s) were used to determine the coverage of electroactive catalyst on the electrode surface; such coverages ranged from 4×10^{-11} to 40×10^{-11} mol/cm^2 and were generally somewhat less than the total amount of catalyst deposited by the droplet evaporation technique.

(5) Randin, J. P. "Encyclopedia of Electrochemistry of the Elements"; Bard, A. J., Ed.; Marcel Dekker: New York, 1976; Vol. VIII, p 172.

(6) (a) Meshitsuka, S.; Ichikawa, M.; Tamaru, K. *J. Chem. Soc., Chem. Commun.* **1974**, 158–159. (b) Takahashi, K.; Hiratsuka, K.; Sasaki, H. *Chem. Lett.* **1979**, 305–308. (c) *Ibid.* **1977**, 1137–1140.

(7) Clack, D. W.; Hush, N. S.; Woolsey, I. S. *Inorg. Chim. Acta* **1976**, *19*, 129–132.

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