due to formation of a foam. Upon completion of the quench, the mixture was vigorously stirred and heated to 65–70 °C for 4 h. The mixture was then allowed to cool to ambient temperature and stirred for 16 h. The product was filtered off and dried under vacuum to afford the lactone as a white solid (320 g, 92%), mp 64–65 °C: ^{13}C NMR ($CDCl_3$) 176.2, 139.7, 133.0, 132.5, 130.8, 127.3, 124.5, 79.6, 30.8, 28.7; IR 2985, 1781, 1600, 1564, 1466, 1405, 1349, 1324, 1299, 1268, 1170, 1131, 1025 cm^{-1}. Anal. Calcd for $C_{10}H_8Cl_2O_2$: C, 51.98; H, 3.49; O, 13.85. Found: C, 52.03; H, 3.42.

4-(3,4-Dichlorophenyl)-4-phenylbutanoic Acid (4). To a well-stirred slurry of benzene (19.5 g, 0.25 mol), aluminum chloride (13.5 g, 0.10 mol), and CH_2Cl_2 (22.5 mL) was added a solution of lactone **3** (23.1 g, 0.10 mol) in CH_2Cl_2 (22.5 mL). The addition was carried out over 15 min, and the temperature rose from 23 to 35 °C. The mixture was stirred for 2 h at ambient temperature and then quenched on ice (100 g) containing hydrochloric acid (20 mL). The resulting acidic mixture was stirred for 15 min. The phases were separated, the organic layer was washed with water, and the methylene chloride was removed by atmospheric distillation. The residual liquid was treated with hexane and allowed to cool to ambient temperature, which resulted in precipitation of a light brown solid. After stirring for 1 h, the product was filtered off and washed with hexane to yield diaryl acid **4** (28.0 g, 91%), mp 121–122 °C: ^{13}C NMR 173.9, 145.9, 143.5, 131.0, 130.6, 129.6, 128.8, 128.7, 128.0, 127.6, 126.5, 48.8, 32.1, 29.5; IR 3665, 3506, 3001, 1711, 1601, 1558, 1491, 1466, 1452, 1399, 1229, 1130, 1027 cm^{-1}. Anal. Calcd for $C_{16}H_{14}Cl_2O_2$: C, 62.15; H, 4.56; O, 10.35. Found: C, 61.96; H, 4.39.

4-(3,4-Dichlorophenyl)-3,4-dihydro-1(2*H*)-naphthalenone (5). A solution of lactone (1.0 g, 0.004 mol), benzene (4.0 mL, 0.045 mol), and sulfuric acid (96%, 5.0 mL, 0.094 mol) at ambient temperature was heated to 95 °C for 1 h and then 140 °C for 1.5 h. After cooling, the reaction was inverse quenched onto ice (40 g). The mixture was stirred for 18 h. The product was filtered off and dried under vacuum to afford the tetralone as a white solid (740 mg, 63%). Similar conditions were employed for methanesulfonic acid [lactone **3** (10.0 g, 0.04mol)], yielding tetralone **5** (7.24 g, 63%).

Reaction conditions for triflic acid are as follows: To a solution of lactone **3** (3.0 g, 0.012 mol) in benzene (6 mL, 0.067 mol) was added triflic acid (5.34 mL, 0.06 mol) at ambient temperature, and the solution was stirred for 5 min and then heated to 75 °C for 1.5 h. After cooling, the reaction was inverse quenched onto ice (20 g) and CH_2Cl_2 (30 mL) was added. The pH was then adjusted to 9.0 with aqueous NaOH (15 mL of a 4 N solution). The organic layer was then separated and the aqueous extracted again with CH_2Cl_2 (30 mL). The organic extracts were combined and dried with $MgSO_4$. The CH_2Cl_2 was distilled off at atmospheric pressure until the volume was reduced to ~40 mL. Hexane (40 mL) was added and the distillation continued until the distillate temperature reached 67 °C, at which point the heating mantle was removed and the contents allowed to crystallize for 16 h. The product was filtered off and dried in a vacuum oven to afford the tetralone **5** (3.22 g, 91%) as a white solid.

Reaction conditions for anhydrous hydrogen fluoride are as follows [*Note: hydrogen fluoride is a colorless, highly irritating, corrosive, and poisonous* gas.[13]]: To a 125-mL Daiflon [poly(trifluoromonochloroethylene)] vessel were added lactone **3** (3.0 g, 0.012 mol) and benzene (6 mL, 0.067 mol). The reaction vessel was then attached to a Daiflon manifold and anhydrous hydrogen fluoride (20 mL, 1.0 mol) was distilled into the vessel at −78 °C. The reaction mixture was then allowed to warm to ambient temperature and stirred for 18 h. The excess hydrogen fluoride and benzene were removed under vacuum and scrubbed with calcium oxide. Methylene chloride (30 mL) and water (15 mL) were added and the pH adjusted to 12 with aqueous NaOH (1.0 N, 13 mL) at 5 °C. The phases were separated, and the aqueous was extracted again with CH_2Cl_2 (30 mL). The combined organic extracts were dried $MgSO_4$, and the solvent was distilled off till the volume was reduced to ~30 mL. Hexane (40 mL) was added and distillation continued until the distillate reached a temperature of 67 °C. The solution was allowed to cool and stirred for 16 h at ambient temperature. The product was filtered off as a white solid and dried under vacuum to afford **5** (3.43 g, 97%), mp 102–3 °C: ^{13}C NMR ($CDCl_3$) 197.3, 144.9, 144.0, 133.9, 132.8, 132.7, 131.0, 130.6, 130.5, 129.3, 128.0, 127.6, 127.4, 44.6, 36.5, 31.7; IR 2997, 2942, 2865, 1682, 1598, 1559, 1466, 1452, 1397, 1345, 1330, 1285, 1132, 1026 cm^{-1}. Anal. Calcd for $C_{16}H_{12}Cl_2O$: C, 66.00; H, 4.15; O, 5.49. Found: C, 65.83; H, 3.89.

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Supplementary Material Available: Experimental data for compounds not described in Experimental Section (1 page). Ordering information is given on any current masthead page.

(13) Merck index, Tenth Edition, 4703.

Isolation of Optically Active Oximes

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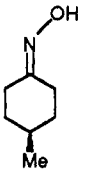
Since the failure of the first attempt of optical resolution of 4-(hydroxyimino)cyclohexanecarboxylic acid by the diastereomeric method using morphine as a chiral base,[1] because of the unstability of the optically active oxime,[1] no further effort for the resolution of the oxime had been carried out. Our success upon optical resolution of various compounds by complexation with optically active host compounds prompted us to attempt the resolution.[2] We now report the isolation of optically active 4-methyl-1-(hydroxyimino)cyclohexane (**1**) and *cis*-3,5-dimethyl-1-(hydroxyimino)cyclohexane (**2**). We also report Beckmann rearrangement of these optically active oximes to optically active ϵ-caprolactams.



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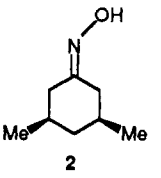

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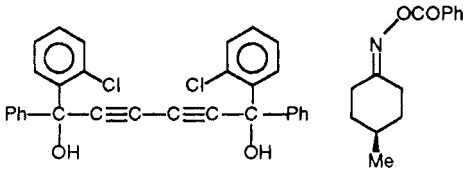
For example, when a solution of racemic 4-methyl-1-(hydroxyimino)cyclohexane (**1a**) and (−)-1,6-bis(*o*-chlorophenyl)-1,6-diphenylhexa-2,4-diyne-1,6-diol (**3b**)[3] in ether–petroleum ether was kept at room temperature, a 1:1 inclusion compound (**4**) of **3b** and (+)-oxime (**1c**) was obtained as colorless needles. Treatment of **4** with allylamine gave a 1:1 inclusion compound of **3b** and allylamine and optically active oxime **1c** of greater than 79% ee. Since the optical purity of the **1c** was not determined directly, its *O*-benzoyl derivative (**5c**) was prepared and its optical purity was determined to be 79% ee by HPLC using a column containing an optically active solid phase, Chiralcel

(1) Mills, W. H.; Bain, A. M. *J. Chem. Soc.* **1910**, *97*, 1866. In this literature, it has been discussed that optically active oxime racemizes through the formation of an oxaziridine intermediate.
(2) Toda, F. *Top. Curr. Chem.* **1987**, *140*, 43.
(3) Toda, F.; Tanaka, K.; Nakamura, K.; Ueda, H.; Ōshima, T. *J. Am. Chem. Soc.* **1983**, *105*, 5151.

0022-3263/90/1955-4973$02.50/0

OC.[4] Therefore, the optical purity of the **1c** can be estimated to be higher than 79% ee. The same treatment of **2a** with **3b** gave a 1:2 inclusion compound (**6**) of **2c** and **3b**, which finally gave **2c** of greater than 59% ee. The optical purity of the **2c** was also estimated by measuring the optical purity of its *O*-benzoyl derivative (**7c**).



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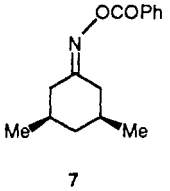

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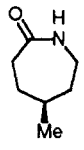
Although the optically active **1** and **2** easily racemize in solution, these compounds are fairly stable in the crystalline state. For example, the half-life of **1c** in $CHCl_3$ (*c* 0.5) at 27–28 °C was about 24 h. However, the half-life time in the crystalline state at 25 °C was estimated to be about 100 days. Furthermore, the **1c** in **4** and the **2c** in **6** are stable in the crystalline state and do not racemize.

In order to determine the optical purity of **1c** and **2c** in **4** and **6**, respectively, more precisely, Beckmann rearrangement of **1c** and **2c** in the inclusion compound was carried out. Heating of **4** with concentrated H_2SO_4 gave (−)-5-methyl-ε-caprolactam (**8c**) of 80% ee. Therefore, it is certain that the optical purity of **1c** in **4** is higher than 80% ee. However, the same treatment of **1c** itself from which **5c** of 79% ee is derived, gave **8c** of 54% ee. Molecules of **1c** in the inclusion crystals of **4** might be sterically restricted to decrease the racemization in the rearrangement. The same treatment of **6** with H_2SO_4 gave (+)-*cis*-3,5-dimethyl-ε-caprolactam (**9c**). Although the optical



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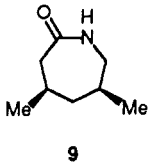

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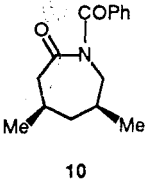

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a: rac
b: (−)
c: (+)

purity of **9c** was not determined, that of its *N*-benzoyl derivative (**10c**) was determined to be 68% ee.

These results give direct evidence for a concerted mechanism for the Beckmann rearrangement. Indirect evidence has been reported, previously, that an optically active alkyl group on the oxime carbon atom migrates to the nitrogen atom without racemization.[5,6]

Experimental Section

General Procedure. All optical purities were determined by HPLC using a column containing an optically active solid phase, Chiralcel OC,[4] and iPrOH–hexane (1:9) as a solvent with the flow rate 0.5 mL/min. In the HPLC analysis, UV detection with the following wavelength was used: 233 nm for **5** and **7**, and 220 and 231.5 nm for **8** and **10**, respectively.

Optical Resolution of 4-Methyl-1-(hydroxyimino)cyclohexane (1) and *cis*-3,5-Dimethyl-1-(hydroxyimino)cyclohexane (2). When a solution of **1a** (1.58 g, 12.4 mmol) and **3b**[3] (3 g, 6.2 mmol) in ether–petroleum ether (1:1, 14 mL) was kept at room temperature for 12 h, a 1:1 inclusion compound of **3b** and **1c** was obtained as colorless needles, which by three recrystallizations from ether–petroleum ether (1:1) gave pure 1:1 inclusion compound **4** (1.48 g, 39%, mp 101–103 °C. Anal. Calcd for $C_{30}H_{20}O_2Cl_2{\cdot}C_7H_{13}ON$: C, 72.78; H, 5.45; N, 2.29. Found: C, 72.92; H, 5.62; N, 2.03. Treatment of **4** with allylamine (0.45 g) in ether–petroleum ether (1:1) at 0 °C for 5 min gave a 1:1 inclusion compound of **3b** and allylamine as colorless needles, which on acidification recovered **3b**. The filtrate left after separation of the inclusion compound was chromatographed on silica gel using $CHCl_3$–AcOEt (9:1) as a solvent to give **1c** (0.23 g, 29%, mp 51–52 °C (lit.[7] mp for **1a** 37–39 °C), $[\alpha]_D$ +57° (*c* 0.5 in $CHCl_3$)). Treatment of the **1c** with benzoyl chloride and pyridine at 0 °C for 10 min gave *O*-benzoyl derivative **5c** in quantitative yield, mp 58–60 °C, $[\alpha]_D$ +70.1° (*c* 0.2 in $CHCl_3$). Anal. Calcd for $C_{14}H_{17}O_2N$: C, 72.70; H, 7.41; N, 6.06. Found: C, 72.89; H, 7.57; N, 5.92. HPLC analysis of **5c** showed the two peaks of the retention time 23.86 and 27.60 min in 89.5:10.5 ratio, from which the optical purity of **5c** was determined to be 79% ee. Finally, the optical purity of the initially obtained **1c** was estimated to be higher than 79% ee.

When a solution of **2a** (1.46 g, 10.3 mmol) and **3b** (5 g, 10.3 mmol) in ether–petroleum ether (1:1, 12 mL) was kept at room temperature for 12 h, a 2:1 inclusion compound of **3b** and **2c** was obtained as colorless needles, which by three recrystallizations from ether–petroleum ether (1:1) gave pure 2:1 inclusion compound **6** (1.94 g, 34%, mp 104–106 °C). Anal. Calcd for $2C_{30}H_{20}O_2Cl{\cdot}C_8H_{15}ON$: C, 73.71; H, 5.00; N, 1.26. Found: C, 73.64; H, 5.29; N, 1.02. Treatment of **6** with allylamine by the same method as that applied for **4** gave **2c** (12%, mp 72–74 °C (lit.[7] mp for **2a** 77–77.5 °C), $[\alpha]_D$ +50° (*c* 0.5 in $CHCl_3$)). Treatment of **2c** with benzoyl chloride by the same method as that applied for **1c** gave **7c** (quantitative yield, mp 69–71 °C, $[\alpha]_D$ +47.5° (*c* 0.4 in $CHCl_3$)). HPLC analysis of **7c** showed the two peaks of the retention time 21.12 and 26.21 min in 20.5:79.5 ratio, from which the optical purity of **7c** was determined to be 59% ee. Finally, the optical purity of the initially obtained **2c** was determined to be higher than 59% ee.

Beckmann Rearrangement of 1c and 2c in the Inclusion Compound with 3b. A mixture of **4** (1 g) and 85% H_2SO_4 (12 mL) was heated at 120–130 °C for 10 min, and the cooled reaction mixture was neutralized with aqueous KOH and extracted with $CHCl_3$. The $CHCl_3$ solution was washed with water and dried over $MgSO_4$. The $CHCl_3$ solution was evaporated, and the residue was distilled in vacuo to give **8c** (0.15 g, 58%, mp 43 °C (lit.[7] mp for **8a** 41–42 °C), $[\alpha]_D$ +14.6° (*c* 1.2 in $CHCl_3$)). HPLC analysis of **8c** showed two peaks of the retention time 46.24 and 52.26 min in 10:90 ratio, from which the optical purity of the **8c** was determined to be 80% ee.

A mixture of **6** (1 g) and 85% H_2SO_4 (12 mL) was heated for 10 min. The reaction mixture was treated as above to give **9b** as colorless crystals (0.08 g, 62%, mp 123–125 °C (lit.[7] mp for **9a** 122–123 °C), $[\alpha]_D$ −8.3° (*c* 0.4 in $CHCl_3$)). Since the optical purity of **9b** was not determined directly, it was determined for its *N*-benzoyl derivative. Treatment of the **9b** with benzoyl chloride in pyridine at 0 °C for 30 min gave **10c** (42%, mp 75–78 °C, $[\alpha]_D$ +82.7° (*c* 0.2 in $CHCl_3$)). Anal. Calcd for $C_{15}H_{19}O_2N$: C, 73.44; H, 7.81; N, 5.71. Found: C, 73.60; H, 7.92; N, 5.53. HPLC analysis of **10c** showed the two peaks of the retention time 33.81 and 37.62 min in 84:16 ratio, from which the optical purity of **10c** was determined to be 68% ee.

Acknowledgment. We wish to thank for the Ministry of Education, Science and Culture, Japan, for Grant-in-Aid for Developmental Scientific Research, No. 63840017.

(4) Chiralcel OC is available from Daicel Chemical Industries, Ltd., Himeji, Japan.
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(6) Kenyon, J.; Young, D. P. *J. Chem. Soc.* **1941**, 263.
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