mL) and was washed with saturated ammonium chloride solution (2 × 100 mL). The organic phase was dried (Na_2SO_4) and concentrated, and the residue was chromatographed (methylene chloride–hexane, 3:2) to afford ester **20** (0.386 g, 94.8%). The ester was purified by crystallization from methanol–water (mp 86 °C): ^{1}H NMR δ 3.75 (s, 3 H, CO_2CH_3), 3.87 (s, 2 H, $CH_2CO_2CH_3$), 3.95 (s, 3 H, OCH_3), 6.80 (s, 1 H, benz[e]indole-6H), 7.605–7.37 (m, 3 H), 8.18 (dd, 2 H, J = 8.35, 1.32 Hz), 8.81 (s, 1 H, NH); IR (cm^{-1}) 3400, 1610, 1600, 1550, 1450, 1380, 1300, 1270, 1200, 1160, 1140, 1100, 1040, 1010, 1000, 980, 950, 820, 790, 750, 715, 700, 640, 630; MS (EI) m/e (relative intensity) 269 (m$^+$, 11.7), 196 (41.2), 69 (10.0), 59 (7.0), 58 (100.0), 57 (17.1). Anal. Calcd for $C_{16}H_{15}NO_3$: C, 71.36; H, 5.61. Found: C, 71.51; H, 5.64.

2,2,2-Trichloro-1,1-dimethylethyl 1-(Carbomethoxymethyl)-5-methoxy-1,2-dihydrobenz[e]indole-3-carboxylate (21). To a solution of methyl ester **20** (250 mg, 0.54 mmol) in glacial acetic acid (20 mL) at 15 °C was added sodium cyanoborohydride (25-mg portions) until no starting material remained by TLC (1.3 equiv). The crude product was poured into water and basified with saturated aqueous sodium bicarbonate to pH 7.5–8.0. The indole was extracted with ether (3 × 100 mL), dried (Na_2SO_4), and concentrated to a pale yellow oil, which was immediately used without purification. The crude indoline was dissolved in acetonitrile (20 mL), cooled in an ice bath, and treated with triethylamine (103 mg, 0.60 mmol), followed by 2,2,2-trichloro-1,1-dimethylethyl chloroformate (144 mg, 0.60 mmol), and 4-(dimethylamino)pyridine (50 mg). The mixture was kept for 12 h at room temperature under a nitrogen atmosphere. The acetonitrile was removed under reduced pressure, and the resulting oil was poured into water (100 mL) and extracted with ether (3 × 100 mL). The etheral layer was washed with 10% H_2SO_4 (2 × 100 mL), dried (Na_2SO_4), concentrated, and chromatographed (2:1 methylene chloride–hexane) to yield carboxylate **21** (270 mg, 76.1%), which was crystallized from methanol (mp 139–140 °C): ^{1}H NMR δ 2.1 (s, 6 H), 2.55–2.68 (m, 2 H), 3.08 (t, 2 H, J = 5.1 Hz), 3.65 (s, 3 H), 4.0 (s, 3 H, OCH_3), 5.02 (br s, 1 H), 7.5–7.2 (m, 3 H), 8.21 (d, 2 H, J = 7.6 Hz); IR (cm^{-1}) 1750, 1680, 1650, 1590, 1510, 1450, 1430, 1380, 1300, 1250, 1200, 1050, 1000, 950, 900, 880, 670, 640; MS (EI) m/e (relative intensity) 477 (m + 2, 13.8), 476 (m + 1, 10.9), 475 (m$^+$, 46.8), 474 (12.2), 473 (40.6), 401 (10.9), 399 (10.4), 272 (25.0), 271 (100.0), 270 (11.7), 256 (15.1), 241 (12.2), 211 (11.2), 210 (53.9), 199 (16.9), 198 (93.7), 197 (71.4), 196 (18.8), 195 (15.3), 183 (16.9), 182 (43.9), 107 (23.4), 154 (14.1), 128 (14.1), 128 (18.1), 127 (23.6), 125 (16.5), 123 (22.7), 91 (15.5), 89 (25.5), 87 (21.9), 77 (12.2), 59 (16.2), 53 (15.8). Anal. Calcd for $C_{21}H_{22}NO_5Cl_3$: C, 58.28; H, 4.59. Found: C, 58.51; H, 4.49.

2,2,2-Trichloro-1,1-dimethylethyl 5-Methoxy-1-(carboxymethyl)-1,2-dihydrobenz[e]indole-3-carboxylate (22). To a solution of ester **21** (318.3 mg, 0.67 mmol) in methanol (10 mL) was added 20% sodium hydroxide (2 mL). The solution was stirred at room temperature until no starting material was present by TLC (ca. 12 h). The reaction mixture was evaporated to dryness. The resulting salt was dissolved in water (50 mL) and acidified to pH 2 with 10% sulfuric acid. The product was extracted with ether, dried (Na_2SO_4), and concentrated to yield **22** (304.3 mg, 98.5%) as an off-white (greenish tint) solid (mp 179–180 °C): ^{1}H NMR δ 2.00 (s, 6 H, $C(CH_3)_2$), 3.94 (s, 3 H, OHC_3), 4.29–4.65 (m, 5 H), 7.30 (s, 1 H), 7.37–7.53 (m, 2 H), 7.6–8.0 (m, 2 H); IR (cm^{-1}) 3500–2800 (b), 1710, 1640, 1590, 14780, 1370, 1300, 1240, 1160, 1130, 1020, 980, 840, 800, 780, 750, 720; MS (EI) m/e (relative intensity) 463 (m + 2, 11.4), 461 (m$^+$, 27.7), 459 (29.2), 315 (12.1), 257 (85.0), 256 (28.2), 255 (37.1), 240 (10.4), 212 (10.7), 211 (40.5), 210 (48.78), 199 (24.0), 198 (100.0), 197 (62.1), 196 (76.9), 195 (18.8), 183 (21.1), 182 (39.8), 168 (13.3), 167 (37.1), 166 (12.1), 154 (14.6), 140 (10.9), 139 (16.0), 128 (21.4), 127 (28.9), 126 (17.0), 125 (10.9), 124 (22.6), 123 (12.9), 111 (13.6), 109. (19.9), 91 (17.7), 89 (49.3), 87 (14.6), 84 (11.2), 77 (13.3), 53 (49.3). Anal. Calcd for $C_{20}H_{20}NO_5Cl_3$: C, 52.13; H, 4.41. Found: C, 52.23; H, 4.49.

2,2,2-Trichloro-1,1-dimethylethyl 5-Methoxy-1-(chloromethyl)-1,2-dihydrobenz[e]indole-3-carboxylate (23). To a solution of **22** (250 mg, 0.54 mmol), DMF (1 drop), and benzene (25 mL) was added oxalyl chloride (0.52 mL, 0.60 mmol). After stirring for 30 min under a nitrogen atmosphere, the yellow-brown solution of acid chloride was evaporated to dryness at room temperature in vacuo. To the resulting oil was added the sodium salt of 2-mecaptopyridine N-oxide (80.5 mg, 0.6 mmol), 4-(dimethylamino)pyridine (10 mg), and carbon tetrachloride (25 mL). The mixture was evacuated, purged with nitrogen (3X), and heated to reflux for 4 h. The cooled solution was filtered, concentrated, and chromatographed (methylene chloride–hexane, 1:1) to yield chloride **23** as a colorless oil (81.1%): ^{1}H NMR δ 2.04 (s, 6 H), 3.57 (dd, 2 H, J = 9.4, 15.7 Hz), 3.96 (dd, J = 2.3, 10.7 Hz), 4.04 (s, 3 H), 4.91–4.87 (m, 1 H), 7.38 (t, 1 H, J = 7.2 Hz), 7.61 (s and d, 2 H, J = 8.5 Hz), 7.52 (t, 1 H, J = 7.45 Hz), 8.22 (d, 1 H, J = 8.4 Hz); IR (cm^{-1}) 1770, 1740, 1605, 1590, 1550, 1450, 1320, 1280, 1210, 1190, 1160, 1100, 1050, 1020, 920, 900, 820, 800, 750, 730, 710; MS (EI) m/e (relative intensity) 451 (m$^+$, 15.8), 449 (11.6, 293 (26.6), 292 (15.5), 291 (100.0), 246 (10.5), 242 (13.8), 198 (26.6), 197 (14.5), 196 (15.5), 182 (15.5), 171 (12.4), 167 (13.8), 159 (12.0), 128 (11.5), 127 (14.2), 125 (10.5), 123 (15.5), 102 (16.8), 100 (14.2), 89 (14.7), 87 (10.1), 84 (14.2), 72 (10.2). Anal. Calcd for $C_{19}H_{19}NO_3Cl_4$: C, 50.52; H, 4.43. Found: C, 50.61; H, 4.49.

***N*-((2,2,2-Trichloro-1,1-dimethylethoxy)carbonyl)-1,2,10,10α-tetrahydrocyclopropa[1,2-*c*]benz[*e*]indol-5-one (4).** To a solution of chloride **23** (39 mg, 0.086 mmol) in 1,2-dichloroethane (5 mL) was added boron trichloride–dimethylsulfide complex (250 mg, excess) in 5 equal portions. The solution was refluxed until no starting material remained (ca. 4 h). The cooled solution was poured into water (20 mL), and the crude product was extracted with methylene chloride (3 × 25 mL), dried (Na_2SO_4), and concentrated. This crude oil was treated with Et_3N (0.5 mL) in CH_3CN (5 mL), and the reaction mixture was stirred vigorously for 3 h (23 °C) under nitrogen. The solvent was removed under reduced pressure, and the oil was washed with methylene chloride–water, and the methylene chloride layer was dried (Na_2SO_4), evaporated at room temperature, and chromatographed CH_2Cl_2–ether (10:1) to yield **4** as a tan colored solid (mp 131 °C): ^{1}H NMR δ 1.3–1.2 (m, 1 H), 1.65 (br s, 2 H), 1.97 (d, 1 H, J = 6.5 Hz), 2.04 (t, 1 H, J = 7.9 Hz), 2.18 (s, 6 H), 7.39 (s, 1 H), 7.8–7.4 (m, 4 H); MS (EI) m/e (relative intensity) 400.7 (m$^+$, 15.8), 279 (18.4), 278 (16.1), 167 (40.5), 150 (10.8), 149 (100.0), 147 (10.7), 129 (35.5), 113 (11.6), 112 (13.2), 84 (17.2), 83 (19.9), 77 (28.1), 71 (26.9), 70 (23.6), 69 (11.6), 57 (33.8). Anal. Calcd for $C_{18}H_{16}NO_3Cl_3$: C, 53.92; H, 4.02. Found: C, 54.01; H, 4.53.

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A Convenient Method for β-Lactam Formation from β-Amino Acids Using Phenyl Phosphorodichloridate Reagent

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In recent years there has been considerable interest in the development of efficient methods for the construction of appropriately substituted azetidin-2-ones because of the importance of β-lactam antibiotics.[1] Although there are a variety of methods for the construction of the β-lactam ring,[2] one of the most useful approaches is based on dehydration of β-amino acids by means of condensing agents.[3,4] Phosphorus reagents are known to be efficient activating agents for the carboxyl group;[5] however, with the exception

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Scheme I

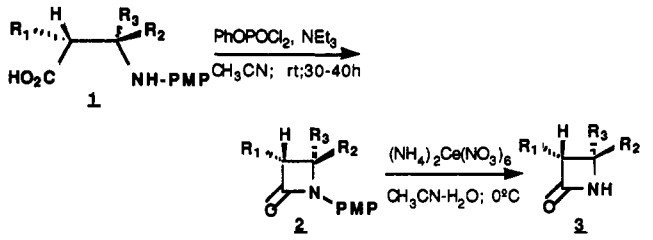


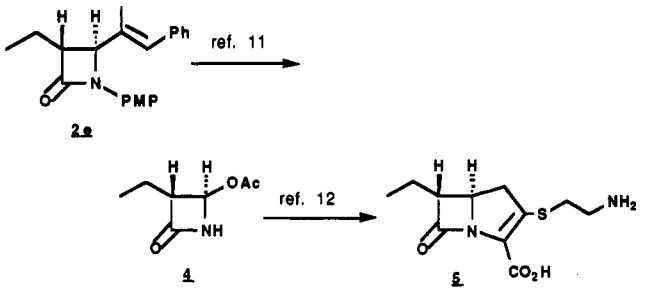
Table I. Preparation of β-Lactams 2 from β-Amino Acids 1, Promoted by $PhOPOCl_2$ Reagent[a]

compd	R_1	R_2	R_3	yield,[b] %	mp,[c] °C
a	Me	PhCH=CMe	H	80	94–95
b	Me	H	PhCH=CMe	78	114–116
c	Me	4-MeC_6H_4	H	80	88–90
d	Me	H	4-MeC_6H_4	80	118–119
e	Et	PhCH=CMe	H	82	oil
f	Et	H	4-MeC_6H_4	85	162–164
g	^{i}Pr	H	PhCH=CH	90	139–142
h	PhO	H	PhCH=CMe	90	157–159
i	PhO	H	PhCH=CH	95	180–182

[a] Reactions carried out at room temperature and conducted on a 2-mmol scale; 1:4:1.1 β-amino acid 1, triethylamine, and phenyl phosphorodichloridate, respectively. [b] Yields based on the weight of isolated product. [c] All β-lactams prepared were racemic mixtures, fully characterized by their physical and spectroscopic data, see ref 11. PMP: *p*-methoxyphenyl group.

of triphenylphosphine-based reagents[6] very little attention has been paid to their application in β-lactam synthesis.[7]

Scheme II



Scheme III

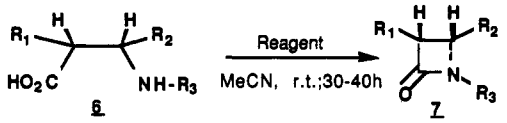


Table II. Preparation of β-Lactams 7 from β-Amino Acids 6, Promoted by Phosphorylating Reagents[a]

compd	R_1	R_2	R_3	reagent	yield,[b] %
a	PhO	PhCH=CH	4-MeC_6H_4	$(PhO)_2POCl$	87
				Me_2NPOCl_2	80
b	H	PhCH=CMe	$PhCH_2$	$(PhO)_2POCl$	88
c	H	PhCH=CH	4-$MeOC_6H_4$	Me_2NPOCl_2	85

[a] Reactions carried out at room temperature on a 2-mmol scale. [b] Yields based on the weight of isolated product.

Among many phosphorylating agents, phenyl phosphorodichloridate has found wide application in most synthetic organic transformations.[8] In previous reports from our laboratory[9] we demonstrated that this reagent, in the presence of an organic base, efficiently produced β-lactams from acetic acids and imines.

In this paper we report that phenyl phosphorodichloridate is very effective for promoting β-lactam formation from β-amino acids. Since a *N*-(*p*-methoxyphenyl) group in β-lactams can be removed under mild conditions, according to the Kronenthal method,[10] the reaction was examined for *N*-(*p*-methoxyphenyl) β-amino acids 1 (Scheme I). When β-amino acids 1 were treated with equimolar amounts of phenyl phosphorodichloridate reagent in acetonitrile as solvent at room temperature for 30–40 h, cyclization proceeded smoothly to give high yields of β-lactams 2. Results are summarized in Table I to

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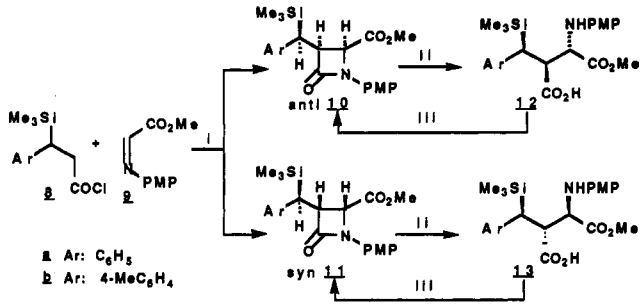
illustrate the efficiency of the method. The reaction works well with both erythro and threo β-amino acids to give the corresponding cis or trans β-lactams, respectively, in excellent yields. Particularly, compound **2e** (Scheme II) that incoporates the ethyl side chain at C_3 position of the β-lactam ring could be further elaborated[11] to the 4-acetoxyazetidin-2-one **4**, as precursor of (±)PS-5 carbapenem antibiotic[12] **5**. On the other hand, compound **2a** could also be elaborated, by established protocols, to the (±)PS-6 carbapenem antibiotic.[1,13]

The cyclization reaction also works well with other phosphorylating reagents (Table II) to provide good to excellent yields of the expected β-lactams. For example, both diphenyl phosphorochloridate and *N,N*-dimethylphosphoramidic dichloride convert β-amino acids **6** into their corresponding β-lactams **7** in yields of 80–88% (Scheme III). Cyclization of α-unsubstituted β-amino acids bearing *N*-aryl substituents is the only case in which we have found the reaction failed; however, the easy separation of β-lactams from the reaction mixture and the use of inexpensive reagents makes the method potentially applicable for a large-scale production of β-lactams. When the reaction was examined in different solvents, acetonitrile gave the best results in terms of chemical yields, although methylene chloride, tetrahydrofuran, and dimethylformamide were also effective. In the last case the reagent forms a Vilsmeier type complex,[8b] but a tedious purification of products was needed. However, when the above complex was first prepared by using a slight excess of dimethylformamide in methylene chloride as solvent, similar results to those obtained by means of phenyl phosphorodichloridate alone were produced. Since the stereochemistry of the β-amino acids was preserved in the cyclization reaction, this procedure has also been used by us to determine unambigously the ratio of isomers produced in a synthetic plan leading to β-amino acids. Bose and co-workers[14] reported that alkaline cleavage of the β-lactam ring provided a route to β-amino acids. However, under these conditions, epimerization at C_3 or C_4 of the β-lactam ring usually takes place, and such a process is not feasible when other base-sensitive groups are involved.[15]

In connection with studies directed toward the synthesis of nonproteinogenic amino acids, a class of compounds that represents an important group of natural products,[16] we found that β-lactams bearing a trialkylsilyl group at the $C_{1'}$ position of the C_3 alkyl side chain are readily cleaved by means of HBF_4–etherate complex at room temperature, leading to substituted aspartic acids without epimerization at any of the three chiral centers. The starting β-lactams were prepared by our recently developed acid chloride–imino ester condensation[17] in yields of 75–90%. Both syn and anti isomers, according to the nomenclature introduced by Masamune,[18] were separated by crystallization from methanol and subjected to treatment with a HBF_4–etherate complex in methylene chloride as solvent and, after usual workup, the corresponding β-amino acids were obtained in nearly quantitative yields. When β-amino acid **12** was allowed to react with phenyl phosphorodichloridate reagent in the presence of triethylamine, the corresponding β-lactam **10** was formed as the sole reaction product. Similarly, **13** furnished the β-lactam **11**, thus confirming the absence of epimerization during β-lactam opening. Particularly noteworthy is that β-lactam cleavage under the reported conditions[14] produced saponification of the methoxycarbonyl group together with side products.

Scheme IV[a]



[a] Reagents and conditions: (i) NEt_3, hexane, reflux, 14–16 h; (ii) HBF_4–Et_2O, CH_2Cl_2, room temperature, 24 h; (iii) $PhOPOCl_2$, NEt_3, CH_3CN, room temperature, 25 h.

The results reported here demonstrate that the inexpensive phenyl phosphorodichloridate reagent and its variants should be valuable in the synthesis of β-lactams of interest.[19,20]

Experimental Section

Melting points were determined on Büchi SMP-20 instrument and are uncorrected. Proton nuclear magnetic resonance spectra and ^{13}C spectra were recorded on a Varian VXR 300 spectrometer. All chemical shifts are reported as δ values (ppm) relative to internal tetramethylsilane. Infrared (IR) spectra were recorded on a Shimadzu IR-435 spectrometer. Mass spectra were obtained using a Shimadzu GCMS-QP2000 spectrometer operated at 70 eV. Microanalytical data were obtained on a Perkin-Elmer 240-C instrument. Commercially available compounds were used in this work without further purification or were prepared by literature procedures. Acetonitrile and hexane were dried and purified by distillation. Tetrahydrofuran was distilled over sodium and benzophenone (indicator). Methylene chloride was shaken with concentrated sulfuric acid, dried over potassium carbonate, and distilled.

4-(Methoxycarbonyl)-1-(4′-methoxyphenyl)-3-[1′-(trimethylsilyl)benzyl]azetidin-2-ones (10a, 11a). To a cooled (0 °C) solution of 3-phenyl-3-(trimethylsilyl)propanoic acid (1.75 g, 7.0 mmol) in methylene chloride (30 mL) was added oxalyl chloride (1.20 mL, 14 mmol) dropwise, and the reaction mixture was stirred at room temperature for 2 h. Then, the volatiles were evaporated in vacuo, the crude acyl halide being dissolved in dry hexane (5 mL). This solution was added dropwise to a cooled (0 °C) mixture of methoxycarbonyl *N*-(4′-methoxyphenyl)imine (0.96 g, 5 mmol) and triethylamine (1.50 mL, 11 mmol) in hexane (10 mL) during 10 min. After the ice bath was removed, the reaction mixture was heated at reflux for 20 h, diluted in meth-

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ylene chloride (50 mL), and washed successively with H_2O (50 mL), 1 M HCl (50 mL), saturated $NaHCO_3$ (50 mL), and H_2O (50 mL). Drying over $MgSO_4$ and evaporation of solvents yielded crude *cis*-4-(methoxycarbonyl)-1-(4'-methoxyphenyl)-3-[1'-(trimethylsilyl)benzyl]azetidin-2-one (1.71 g, 86% based on the imine) as a mixture of anti and syn epimers (molar ratio 70:30, respectively). Crystallization from methanol afforded pure *cis-anti*-**10a** isomer (1.03 g, 52%). Mp: 144-145 °C. ^1H NMR ($CDCl_3$): δ 7.30-7.14 (m, 5 H, arom), 6.97 (d, J = 9.3 Hz, 2 H, arom), 6.86 (d, J = 9.3 Hz, 2 H, arom), 4.49 (d, J = 5.4 Hz, 1 H, C*H*COOMe), 4.30 (dd, J = 5.4 Hz, J = 13.5 Hz, 1 H, C*H*CO), 3.79 (s, 3 H, OMe), 3.28 (s, 3 H, OMe), 2.75 (d, J = 13.5 Hz, 1 H, C*H*SiMe$_3$), 0.08 (s, 9 H, SiMe$_3$). ^{13}C NMR ($CDCl_3$): δ 169.5, 164.7, 156.2, 140.9, 131.0, 128.3, 127.2, 125.2, 117.6, 114.1, 55.6, 55.4, 55.3, 52.2, 32.8, -1.9. MS: m/e 397 (M^+). Anal. Calcd for $C_{22}H_{27}NO_4Si$: C, 66.48; H, 6.85; N, 3.52. Found: C, 66.40; H, 6.85; N, 3.35.

Finally, column chromatography (silica gel; eluent, hexane-methylene chloride, 5:1) of mother liquors afforded the *cis-syn*-**11a** isomer (0.45 g, 24%). Syrup. ^1H NMR ($CDCl_3$): δ 7.31-7.10 (m, 5 H, arom), 6.97 (d, J = 9.3 Hz, 2 H, arom), 6.86 (d, J = 9.3 Hz, 2 H, arom), 4.55 (d, J = 6.3 Hz, 1 H, C*H*COOMe), 4.15 (dd, J = 6.3 Hz, J' = 3.6 Hz, 1 H, C*H*CO), 3.79 (s, 3 H, OMe), 3.12 (s, 3 H, OMe), 2.58 (d, J = 3.6 Hz, 1 H, C*H*SiMe$_3$), 0.10 (s, 9 H, SiMe$_3$). ^{13}C NMR ($CDCl_3$): δ 168.9, 165.9, 156.2, 131.3, 129.3, 128.0, 125.3, 118.0, 114.4, 55.4, 55.0, 52.0, 35.2, 29.7, -2.2. MS: m/e 397 (M^+). Anal. Calcd for $C_{22}H_{27}NO_4Si$: C, 66.48; H, 6.85; N, 3.52. Found: C, 66.31; H, 6.92; N, 3.38.

Compounds **10b** and **11b**. The above method was followed starting from 3-*p*-tolyl-3-(trimethylsilyl)propanoic acid to afford *cis-anti*-4-(methoxycarbonyl)-1-(4'-methoxyphenyl)-3-[*p*-tolyl-(trimethylsilyl)methyl]azetidin-2-one (**10b**) (1.08 g, 54%) [Mp: 154-155 °C (MeOH). ^1H NMR ($CDCl_3$): δ 7.21 (d, 2 H, arom), 7.06 (d, 2 H, arom), 6.86 (d, 2 H, arom), 6.83 (d, 2 H, arom), 4.48 (d, 1 H, J = 5.5 Hz, C*H*COOMe), 4.27 (dd, 1 H, J = 5.5 Hz, J' = 13.5 Hz, C*H*CON), 3.70 (s, 3 H, OMe), 3.31 (s, 3 H, COOMe), 2.70 (d, 1 H, J = 13.5 Hz, C*H*SiMe$_3$), 2.32 (s, 3 H, C*H*$_3$Ar), 0.06 (s, 9 H, SiMe$_3$). ^{13}C NMR ($CDCl_3$): δ 169.5, 164.8, 156.2, 137.6, 134.6, 131.1, 129.0, 127.1, 117.6, 114.5, 55.8, 55.2, 52.2, 32.3, 20.9, -2.9. MS: m/e 411 (M^+). Anal. Calcd for $C_{23}H_{29}NO_4Si$: C, 67.12; H, 7.10; N, 3.40. Found: C, 66.98; H, 7.11; N, 3.07.] and *cis-syn*-4-(methoxycarbonyl)-1-(4'-methoxyphenyl)-3-[*p*-tolyl(trimethylsilyl)methyl]azetidin-2-one (**11b**) (0.51g, 25%). Syrup. ^1H NMR ($CDCl_3$): δ 7.28 (d, 2 H, arom), 7.03 (d, 2 H, arom), 6.85 (m, 4 H, arom), 4.48 (d, 1 H, J = 6.3 Hz, C*H*CN), 4.08 (dd, 1 H, J = 6.3 Hz, J' = 3.6 Hz, C*H*CON), 3.75 (s, 3 H, OMe), 2.51 (d, 1 H, J = 3.6 Hz, C*H*SiMe$_3$), 2.23 (s, 3 H, ArC*H*$_3$), 0.06 (s, 9 H, SiMe$_3$). ^{13}C NMR ($CDCl_3$): δ 168.9, 165.9, 156.2, 135.1, 134.7, 131.3, 129.2, 128.7, 118.0, 114.1, 55.5, 55.1, 51.9, 34.6, 29.7, 20.9, -2.2. MS: m/e 411 (M^+). Anal. Calcd for $C_{23}H_{29}NO_4Si$: C, 67.12; H, 7.10; N, 3.40. Found: C, 67.08; H, 7.34; N, 3.30.

Methyl 3-Carboxy-2-((4'-methoxyphenyl)amino)-4-phenyl-4-(trimethylsilyl)butanoate (12). To a solution of *cis-anti*-4-(methoxycarbonyl)-1-(4'-methoxyphenyl)-3-[1'-(trimethylsilyl)benzyl]azetidin-2-one (**10a**) (0.766 g, 2 mmol) in methylene chloride (7 mL) cooled to 0 °C, was added, with stirring, $HBF_4{\cdot}2Et_2O$ (1.68 mL, 10 mmol), and the mixture was stirred at room temperature overnight. It was then diluted with methylene chloride (15 mL) and washed rapidly with cold water (10 mL) and could brine (2 × 10 mL) and dried. Concentration in vacuo gave the crude methyl 3-carboxy-2-((4'-methoxyphenyl)-amino)-4-phenyl-4-(trimethylsilyl)butanoate (**12**) (0.67 g, 83%). Mp: 116-118 °C. ^1H NMR ($CDCl_3$): δ 7.38-7.20 (m, 5 H, arom), 6.75 (d, J = 9 Hz, 2 H, arom), 6.53 (d, J = 9 Hz, arom), 4.08 (d, J = 3.3 Hz, 1 H, C*H*COOMe), 3.76 (s, 3 H, OMe), 3.67 (s, 3 H, OMe), 3.63 (dd, J = 3.3 Hz, J' = 12.6 Hz, C*H*COOH), 2.79 (d, J = 12.6 Hz, 1 H, C*H*SiMe$_3$), 0.06 (s, 9 H, SiMe$_3$). Anal. Calcd for $C_{22}H_{29}NO_6Si$: C, 64.32; H, 7.23; N, 3.26. Found: C 64.41; H, 7.41; N, 3.34.

Cyclization of β-Amino Acids. General Procedure. To a cooled (0 °C) solution of β-amino acid (2.0 mmol) and triethylamine (0.92 mL, 6.5 mmol) in acetonitrile (8 mL), were added phenyl phosphorodichloridate (0.33 mL, 2.2 mmol) and acetonitrile (5 mL). After the resulting solution was stirred for 30-40 h at room temperature, the mixture was diluted with methylene chloride (20 mL) and washed successively with H_2O (10 mL), 1 M HCl (10 mL), saturated $NaHCO_3$ (10 mL), and H_2O (10 mL). Drying over $MgSO_4$ and evaporation of solvents yielded crude β-lactam, which was purified by crystallization or flash chromatography.

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Supplementary Material Available: Characterizing spectra of **10a**, **10b**, **11a**, and **11b** (16 pages). Ordering information is given on any current masthead page.

The Bridged Methylenedihydroanthracenes: *p*-Cyclophane Tautomers

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The tautomers of the simplest alkyl-substituted aromatic compounds toluene, 1-methylnaphthalene, and 9-methylanthracene are all known[1] and are all substantially less stable than their fully aromatic counterparts. The tautomers of 9-methylanthracene are closest in stability but still differ by ca. 40 kJ/mol.[2] Experiment[3] and theory[2] are in agreement that the energy of the methylene tautomer approaches, but never reaches, the energy of the fully aromatic tautomer as the number of annelated rings increases. In anthracenes, substitution at the vinyl and/or peri positions has afforded a number of easily isolable compounds, many of which have been shown to undergo boat-to-boat interconversion on the NMR time scale.[4-7] Also, in some very crowded anthracenes the methylenedihydroanthracene tautomer has been shown to be the more stable tautomer by equilibration in the presence of acid or base.[8] No computational or experimental studies have focused on the bridged counterparts of these compounds, i.e., the exomethylene tautomers of [*n*]-cyclophanes. The [*n*](9,10)anthracenophanes provide an attractive starting point since they have the greatest likelihood of exomethylene-cyclophane tautomeric pairs of similar energy.

Recently we found that deuteration of 3,6-diketo[8]-(9,10)anthracenophane (**1**) in the presence of acid led to incorporation of deuterium at the benzylic positions as well as in the positions α to the carbonyl groups.[9] The likely pathway under these conditions includes the bridged methylenedihydroanthracene (MDA) tautomer **2** as an intermediate. The bridged MDA, in this instance, is the less stable tautomer since there was no evidence (NMR) for its existence in the deuterated sample of **1**. However, since interactions within the bridge of [*n*](9,10)-anthracenophanes, and presumably their MDA tautomers, make significant contributions to the energies of these

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