Acknowledgment. Partial financial support provided by a Presidential Young Investigator Award from the National Science Foundation (CHEM-8958027), the donors of the Petroleum Research Fund, administered by the American Chemical Society (21923-G3), the North Carolina Board of Science and Technology (89SE06), and the Department of Chemistry at the University of North Carolina at Chapel Hill is gratefully acknowledged. Partial funds for equipping the single-crystal X-ray diffraction facility at UNC-CH were provided by the National Science Foundation (CHE-8919288).

Supplementary Material Available: Details of the preparation and characterization of compounds **1**, **2**, **3a,b**, and **4a,b** and listings of complete crystallographic data and results for $Fe_3(CO)_9[\mu_3\text{-}PFe(CO)_2Cp]_2$ (**2**) and $Fe_3(CO)_9[\mu_3\text{-}PFe(CO)_2Cp][\mu_3\text{-}PFe(CO)_2(C_5Me_5)]$ (**4b**) (23 pages); listing of observed and calculated structure factors for **2** and **4b** (36 pages). Ordering information is given on any current masthead page.

Intramolecular Schmidt Reaction of Alkyl Azides

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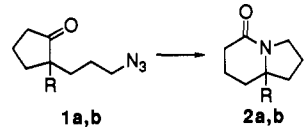
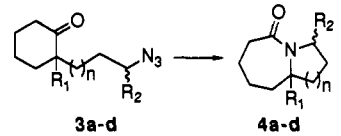
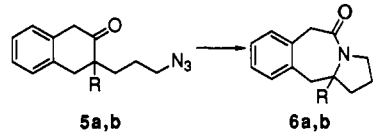
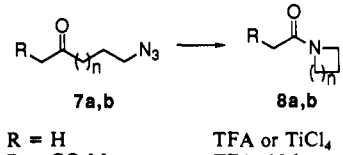
The reaction of hydrazoic acid with ketones to afford a ring-expanded lactam (the Schmidt reaction) is an important method for the preparation of nitrogen-containing heterocycles.[1] The extension of the reaction to provide N-substituted lactams would be particularly useful;[2] however, attempts to replace hydrazoic acid with alkyl azides under classical Schmidt conditions (strong acid) were generally unsuccessful.[1,3] In a series of papers in the late 1950s, Boyer and co-workers did manage to establish a narrow range of azides that react with aromatic aldehydes, but the bona fide migration of an alkyl group was not observed in any of these examples.[4,5] In addition, the intramolecular reaction of several enones with azides gave Schmidt-type products upon thermolysis, but the reaction proceeds by initial attack of the azide upon the double bond followed by rearrangement of the resulting triazoline.[6]

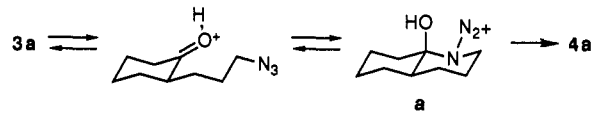
An intramolecular Schmidt reaction of the type shown in eq 1 would constitute an attractive entry into ring systems sporting a nitrogen atom at one of the ring fusion positions. Such ring systems are prominent substructures in a wide variety of alkaloid families.[7] We report that *the intramolecular reaction of alkyl azides with ketones can be accomplished in high yield under remarkably mild and straightforward reaction conditions.*

Table I. Intramolecular Reactions of Alkyl Azides with Ketones

entry	compounds	conditns[a]	yield, %
	 **1a,b** **2a,b**		
1	**a**, R = H	TFA, 40 min	83
2	**b**, R = CO_2Me	TFA, 16 h	66
3	**b**	$TiCl_4$, CH_2Cl_2, 20 min	70
	 **3a-d** **4a-d**		
4	**a**, R_1 = H, R_2 = H, n = 1	TFA, 10 min	90
5	**b**, R_1 = CO_2Et, R_2 = H, n = 1	TFA, 1 h	93
6	**c**, R_1 = H, R_2 = H, n = 2	TFA, 24 h	0
7	**c**	$TiCl_4$, CH_2Cl_2, 16 h	91
8	**d**, R_1 = H, R_2 = CH_3, n = 1	TFA, 20 min	74
	 **5a,b** **6a,b**		
9	**a**, R = H	TFA, 20 min	91
10	**b**, R = CH_3	TFA, 20 min	91
	 **7a,b** **8a,b**		
11	**a**, n = 1, R = H	TFA or $TiCl_4$	0
12	**b**, n = 2, R = CO_2Me	TFA, 12 h	66
13	**b**	$TiCl_4$, 15 min	64

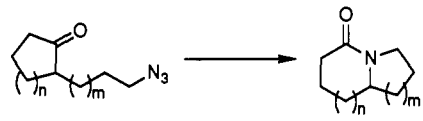
[a] All reactions were carried out at room temperature.

Scheme I



a

The reaction of alkyl azide **5b**[8] is representative of the examples collected in Table I (entry 10). Gas evolution was immediately observed upon dissolution of **5b** in trifluoroacetic acid (TFA).[9]



(1)

(1) (a) Wolff, H. *Org. React. (N.Y.)* **1946**, *3*, 307-336. (b) Smith, P. A. S. In *Molecular Rearrangements*; de Mayo, P., Ed.; John Wiley and Sons: New York, 1963; Vol. 1, pp 457-591. (c) Uyeo, S. *Pure Appl. Chem.* **1963**, *7*, 269-283. (d) Abramovich, R. A.; Kyba, E. P. In *The Chemistry of the Azido Group*; Patai, S., Ed.; John Wiley and Sons: London, 1971; pp 221-329. (e) Banthorpe, D. V. In *The Chemistry of the Azido Group*; Patai, S., Ed.; John Wiley and Sons: London, 1971; pp 397-440. (f) Kyba, E. P. In *Azides and Nitrenes: Reactivity and Utility*; Scriven, E. F. V., Ed.; Academic: Orlando, 1984; pp 2-34.

(2) For a list of methods that allow the formal insertion of a primary amine into a carbonyl compound, see: Hoffman, R. V.; Salvador, J. M. *Tetrahedron Lett.* **1989**, *30*, 4207-4210.

(3) (a) Briggs, L. H.; De Ath, G. C.; Ellis, S. R. *J. Chem. Soc.* **1942**, 61-63. (b) Smith, P. A. S. *J. Am. Chem. Soc.* **1948**, *70*, 320-323.

(4) (a) Boyer, J. H.; Hamer, J. *J. Am. Chem. Soc.* **1955**, *77*, 951-954. (b) Boyer, J. H.; Canter, F. C.; Hamer, J.; Putney, R. K. *J. Am. Chem. Soc.* **1956**, *78*, 325-327. (c) Boyer, J. H.; Morgan, L. R., Jr. *J. Am. Chem. Soc.* **1958**, *80*, 2020-2021. (d) Boyer, J. H.; Morgan, L. R., Jr. *J. Am. Chem. Soc.* **1959**, *81*, 3369-3372. (e) Boyer, J. H.; Morgan, L. R., Jr. *J. Org. Chem.* **1959**, *24*, 561-562.

(5) The "intramolecular Schmidt reactions" described by Boyer do not involve a C → N migration per se, but probably involve the elimination of a proton and N_2.[4a,b] Hydride migrations were observed in the reactions of certain aryl aldehydes and alkyl azides, but yields were low, and the scope of the reaction was severely limited.[4c] To our knowledge, the successful insertion of an alkyl azide into a ketone has never been accomplished.

(6) (a) Schultz, A. G.; Ravichandran, R. *J. Org. Chem.* **1980**, *45*, 5008-5009. (b) Schultz, A. G.; McMahon, W. G. *J. Org. Chem.* **1984**, *49*, 1676-1678.

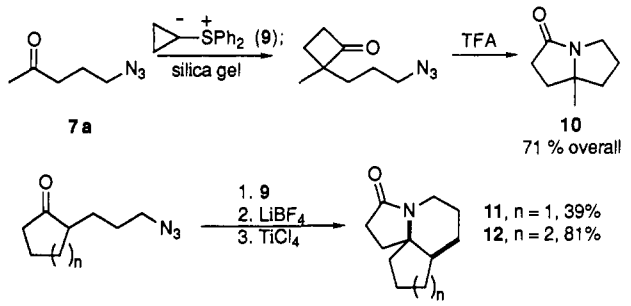
(7) Some recent reviews have appeared. (a) Indolizidine and quinolizidine alkaloids: Herbert, R. B. In *Alkaloids: Chemical and Biological Perspectives*; Pelletier, S. W., Ed.; John Wiley and Sons: New York, 1985; Vol. 3, pp 241-273. (b) Elbein, A. D.; Molyneux, R. J. In *Alkaloids: Chemical and Biological Perspectives*; Pelletier, S. W., Ed.; John Wiley and Sons: New York, 1987; Vol. 5, pp 1-54. (c) Phenanthroindolizidine alkaloids: Gellert, E. In *Alkaloids: Chemical and Biological Perspectives*; Pelletier, S. W., Ed.; John Wiley and Sons: New York, 1987; Vol. 5, pp 55-131. (d) Cephalotaxine alkaloids: Hudlicky, T.; Kwart, L. D.; Reed, J. W. In *Alkaloids: Chemical and Historical Perspectives*; Pelletier, S. W., Ed.; John Wiley and Sons: New York, 1987; Vol. 5, pp 639-690. (e) Pyrrolizidine alkaloids: Robins, D. J. *Adv. Heterocycl. Chem.* **1979**, *24*, 247-291.

(8) The azido ketones were prepared using standard chemistry; details will be provided in the full account of this work.

(9) For the use of trichloroacetic acid in the Schmidt reaction: (a) Reference 3b. (b) Fikes, L. E.; Shechter, H. *Tetrahedron Lett.* **1976**, 2525-2528.

0002-7863/91/1513-8965$02.50/0

Scheme II



After the solution was allowed to stand for ca. 20 min at room temperature, the solvent was removed in vacuo, the residue subjected to a standard basic workup, and the product purified by column chromatography.[10,11] We have also determined that titanium tetrachloride (3.6–4.5 equiv) in CH_2Cl_2 is an excellent reagent for this transformation (cf. entries 2 vs 3, 6 vs 7, and 12 vs 13 in Table I).

A span of four atoms between the carbonyl group and the azide proved optimal (cf. entries 4 vs 6 and 11 vs 12). Thus, whereas **3a** reacted smoothly in TFA, similar treatment of **3c** resulted only in slow decomposition of the azide. Although a low yield of lactam **4c** could be obtained by prolonged dissolution in neat $BF_3{\cdot}OEt_2$, excellent results were realized when $TiCl_4$ was used. In addition, the insertion of a secondary azide proceeded uneventfully, demonstrating that the reaction was not overly sensitive to steric bulk as this site (entry 8).

Although we have not yet carried out detailed mechanistic studies, we favor the sequence of events drawn for the conversion **3a** → **4a** (Scheme I). The nucleophilic attack of the azide upon the protonated ketone is precedented in Boyer's work.[4] A comparison of entries 1 and 2 suggests that the reaction does not involve initial decomposition of the azide moiety: whereas the reaction **1a** → **2a** is complete within 1 h, treatment of **1b** in TFA for 1 h leads to the recovery of >90% starting material. We note that this mechanism is also consistent with higher reactivity of the four-carbon tether, because the antiperiplanar arrangement of the migrating bond and N_2^+ in intermediate **a** is ideally disposed for a stereoelectronically favored migration step.

We also demonstrate that this methodology should prove particularly useful for the rapid construction of complex ring systems when used in conjunction with modern methods of carbocycle synthesis (Scheme II). The addition of diphenylsulfonium cyclopropylide[12] to ketone **7a**, silica gel triggered rearrangement, followed by treatment with TFA gave the bicyclic lactam **10** in 71% overall yield. Two other tandem spiroannulation/ring adjustment reactions are also shown; lactams **11** and **12** were obtained as single diastereomers in the overall yields noted.

These examples demonstrate that the intramolecular Schmidt reaction is likely to have wide utility in the construction of polycyclic, nitrogen-containing materials. We are currently involved in the delineation of the scope of this process and its application to problems in alkaloid synthesis.

Acknowledgment. This work was supported by the National Institutes of Health. J.A. acknowledges an Eli Lilly granteeship (1989–1991).

Supplementary Material Available: Representative experimental procedures (3 pages). Ordering information is given on any current masthead page.

(10) The structure of **6b** was verified by X-ray crystallography to prove the regiochemistry of the reaction; details will be provided in the full paper. We thank Dr. Fusao Takusagawa of the University of Kansas Department of Chemistry for carrying out this determination.

(11) The conversion **5b** → **6b** could also be realized in 90% yield using 1.6 equiv of $BF_3{\cdot}OEt_2$ in CH_2Cl_2.

(12) See: Trost, B. M.; Scudder, P. H. *J. Am. Chem. Soc.* **1977**, *99*, 7601–7610 and references contained therein.

First Application of Attractive Intramolecular Interactions to the Design of Chiral Catalysts for Highly Enantioselective Diels–Alder Reactions

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The utility of chiral 1,3,2-oxazaborolidines[1] and 1,3,2-diazaborolidines[2] as catalysts in enantioselective synthesis has encouraged us to seek new members of this class which achieve selectivity through *attractive* interaction as well as the usual steric repulsion. This note describes a successful and practical methodology based on this approach, which we believe has wide implications in catalyst design and which deals specifically with catalysis of the Diels–Alder reaction.[3] Conceptually, we envisaged the possibility that the (*S*)-tryptophan-derived oxazaborolidine **1** would facilitate the Diels–Alder pathway represented by the transition-state assembly **2**, in which an attractive donor–acceptor interaction favors coordination of the dienophile at the face of boron which is cis to the 3-indolylmethyl substituent. In complex **2**, the π-basic indole and the π-acidic dienophile can assume a parallel orientation at the ideal separation (3 Å) for donor–acceptor interaction.[4] The product from such a catalytic reaction of cyclopentadiene, 2-bromoacrolein, and **1** is expected to be (2*R*)-2-bromobicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (**3**). As described below, this surmise has been confirmed by experiment.

Reaction of *N*-(*p*-toluenesulfonyl)-(*S*)-tryptophan[5] with *n*-$BuB(OH)_2$ in 2:1 toluene–THF at reflux[6] with removal of water (CaH_2 in a Soxhlet thimble) gave after 6 h a solution of catalyst **1**, R = *n*-Bu, which showed a single ^{11}B NMR peak at 34 ppm (downfield from external $BF_3{\cdot}Et_2O$).[7] A solution of catalyst **1**, R = H,[7] was prepared in CH_2Cl_2 or $CDCl_3$ by the reaction of *N*-(*p*-toluenesulfonyl)-(*S*)-tryptophan with 1 equiv of $BH_3{\cdot}THF$ at 23 °C for 10 min (H_2 evolved immediately upon mixing). In the presence of 5 mol % of **1**, R = *n*-Bu, 2-bromoacrolein[8] and cyclopentadiene (ca. 5 equiv) underwent smooth Diels–Alder addition (−78 °C, 1 h) to give the (*R*)-bromo aldehyde **3** in 95% yield, 200:1 (R/S) enantioselectivity, and 96:4 (exo/endo CHO) diastereoselectivity; *N*-tosyltryptophan was efficiently recovered.[9]

(1) (a) Corey, E. J.; Bakshi, R. K.; Shibata, S. *J. Am. Chem. Soc.* **1987**, *109*, 5551–5553. (b) Corey, E. J.; Bakshi, R. K.; Shibata, S.; Chen, C. P.; Singh, V. K. *J. Am. Chem. Soc.* **1987**, *109*, 7925–7926. (c) Corey, E. J.; Shibata, S.; Bakshi, R. K. *J. Org. Chem.* **1988**, *53*, 2861–2863. (d) Corey, E. J.; Bakshi, R. K. *Tetrahedron Lett.* **1990**, *31*, 611–614.

(2) Corey, E. J. *Pure Appl. Chem.* **1990**, *62*, 1209–1216.

(3) For previous studies of catalytic enantioselective Diels–Alder reactions, see: (a) Iwasawa, N.; Sugimori, J.; Kawase, Y.; Narasaka, K. *Chem. Lett.* **1989**, 1947–1950, and references cited. (b) Corey, E. J.; Imwinkelried, R.; Pikul, S.; Xiang, Y. B. *J. Am. Chem. Soc.* **1989**, *111*, 5493–5495. (c) Furuta, K.; Shimizu, S.; Miwa, Y.; Yamamoto, H. *J. Org. Chem.* **1989**, *54*, 1481–1483. (d) Takemura, H.; Komeshima, N.; Takahashi, I.; Hashimoto, S.-I.; Ikota, N.; Tomioka, K.; Koga, K. *Tetrahedron Lett.* **1987**, *28*, 5687–5690. (e) Hashimoto, S.-I.; Komeshima, N.; Koga, K. *J. Chem. Soc., Chem. Commun.* **1979**, 437–438. (f) Takasu, M.; Yamamoto, H. *Synlett* **1990**, 194–196. (g) Sartor, D.; Saffrich, J.; Helmchen, G. *Synlett* **1990**, 197–198. (h) Corey, E. J.; Imai, N.; Zhang, H.-Y. *J. Am. Chem. Soc.* **1991**, *113*, 728–729.

(4) The expectation that **1** should be an effective accelerant for Diels–Alder reaction was strengthened by previous observations in our laboratory[2,3b] and that of Yamamoto.[3c]

(5) Prepared from (*S*)-tryptophan and 2.5 equiv of triethylamine in 10:1 H_2O–THF solution (0 °C) by addition of *p*-toluenesulfonyl chloride in THF and reaction at 23 °C for 3 h; mp 138–139 °C; $[\alpha]^{23}_D$ −42° (*c* 1, EtOH); 88%. The enantiomer was synthesized from (*R*)-tryptophan similarly.

(6) All reactions were performed under an inert atmosphere (Ar or N_2) and with rigorously dried solvents and glassware.

(7) The ^{11}B NMR data are consistent with structure **1**, R = *n*-Bu, as the major species.[1a] In the case of the BH_3-derived catalyst the ^{11}B NMR peak appears at 32.1 ppm.

(8) (a) Corey, E. J.; Snider, B. B. *J. Am. Chem. Soc.* **1972**, *94*, 2549–2550. (b) Prepared from acrolein by addition of Br_2 in CH_2Cl_2 at −78 °C and subsequent reaction with Et_3N; bp 50 °C (30 Torr).

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