Enolboration. 7. Dicyclohexyliodoborane, a Highly Stereoselective Reagent for the Enolboration of Tertiary Amides. Effects of Solvent and Aldolization Temperature on Stereochemistry in Achieving the Stereoelective Synthesis of either Syn or Anti Aldols[1]

Kumaraperumal Ganesan and Herbert C. Brown*

H. C. Brown and R. B. Wetherill Laboratories of Chemistry, Purdue University, West Lafayette, Indiana 47907-1393

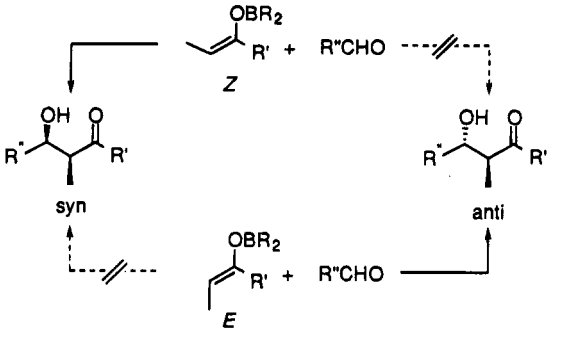
Received May 17, 1994 (Revised Manuscript Received September 26, 1994®)

A highly stereoselective enolboration of tertiary amides has been accomplished for the first time with dicyclohexyliodoborane, Chx_2BI. A systematic study of the enolboration of representative *N,N*-dialkylpropionamides ($CH_3CH_2CONR'_2$) with Chx_2BI in the presence of various tertiary amines of variable steric requirements revealed an unusual aldol stereoselectivity in different solvents and at different aldolization temperatures. Both the nature of solvent and the aldolization temperature influence the stereochemistry of enolboration, with the solvent effect being greater than that of the temperature. Aliphatic and alicyclic hydrocarbon solvents favor formation of the syn aldols from the enol borinates by aldolization at lower temperature (−78 °C), whereas most of the other solvents examined, such as aromatic and chlorinated aliphatic solvents, favor formation of the anti aldols by aldolization at relatively higher temperatures (0 or 25 °C). The remarkable effects of both temperature and solvent in the case of tertiary amides raise a question about the validity of the previously assumed constancy of the *Z* to syn and *E* to anti relationship, suggesting either a possible isomerization of enol borinates with temperature or a different aldolization transition state with different solvent. While the effect of steric requirements of the dialkylamino group of the tertiary amide does not contribute significantly to the stereochemistry, that of the amine exerts a considerable influence. The present study establishes a simple procedure for the stereoselective synthesis of either syn or anti aldols from representative tertiary amides merely by changing the solvent and the aldolization temperature.

Extensive research has been done over the last three decades to develop new reagents and new methodologies for the regio- and stereocontrolled construction of carbon–carbon bonds.[2] Without doubt, the aldol reaction has emerged as one of the more powerful tools for stereocontrol in acyclic systems.[3] Unlike other metal enolates, boron enolates are highly stable and exceptionally stereoselective. Koster has demonstrated that *Z* enol borinates give syn aldols and *E* enol borinates give anti aldols stereoselectively (Scheme 1).[4] Similar stereoselectivity has also been confirmed from our studies[5,6] and by other groups.[7–10]

Many R_2BX reagents (X = OTf, OMs, I, Br, and Cl) have been developed on the basis of Mukaiyama's methodology (eq 1) and employed for the enolboration of ketones and various carbonyl compounds.[5–10] However, essentially no reagent was available for the enolboration

Scheme 1



® Abstract published in *Advance ACS Abstracts,* November 15, 1994.

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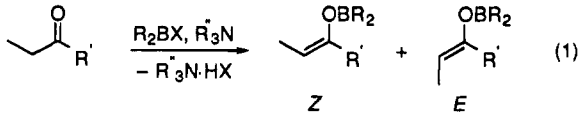
of tertiary amides, except for *n*-Bu_2BOTf which had been shown to enolize a special class of highly reactive tertiary amides, the *N,N*-dialkyl-2,3,3,3-tetrafluoropropanamides.[11a]



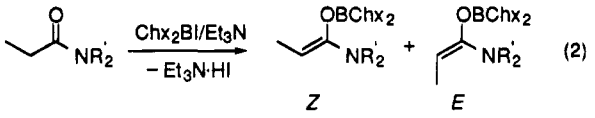
(1)

The stereoselective synthesis of 3-hydroxy-2-methyl esters and amides, the aldol products from the corresponding enolates derived from the propionate esters and propionamides, is highly desirable since these aldol units appear repeatedly in the framework of many natural products.[11b] The lack of simple and effective reagents for the stereoselective enolboration of esters and tertiary amides encouraged us to explore new reagents. Our systematic investigation of the enolboration with various B-X-9-BBN and Chx_2BX reagents (X = OTf, OMs, I, Br, and Cl) established dicyclohexyliodoborane, Chx_2BI, as the most favorable reagent for the enolboration of esters and tertiary amides.[12] Our preliminary investigation of the enolization of representative tertiary amides with Chx_2BI/Et_3N was highly promising for achieving stereoselective aldols, which encouraged us to examine systematically this versatile reagent for the representative tertiary amides.

Results and Discussion

Dicyclohexyliodoborane, Chx_2BI, has been systematically investigated in the present study for the enolboration of tertiary amides, a less reactive but more important class of carbonyl compounds.

Unusual Stereoselectivity. The enolboration experiments are usually carried out in CCl_4 since the ^1H NMR spectra can be directly recorded for the reaction mixture.[6] Wherever the aldolization is to be performed at low temperatures, such as −78 °C, the corresponding enolization is carried out in hexane. In the present study, the enolizations of representative *N,N*-dialkylpropionamides with Chx_2BI/Et_3N (eq 2) were carried out both in CCl_4 and in hexane and then the aldolization was performed with benzaldehyde to determine the syn/anti ratio using the standard technique.[6]



(2)

The results in Table 1 reveal an unusual stereoselectivity under different reaction conditions. For example, the enolization in hexane at 0 °C and the corresponding aldolization with PhCHO at −78 °C give syn aldol, while carrying out both the enolization and the aldolization in CCl_4 at 0 °C yields anti aldol stereoselectively (Scheme 2).

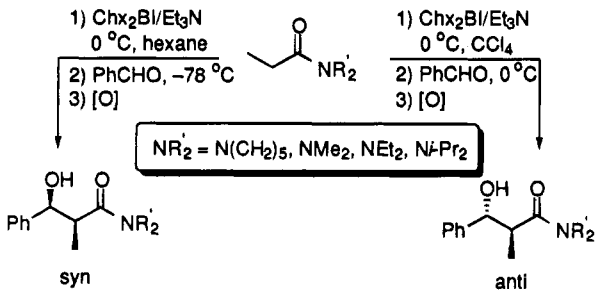
We have already established that nonpolar solvents, such as hexane and CCl_4, behave almost similarly in the enolboration of ketones with Chx_2BCl/Et_3N at various aldolization temperatures.[6c] In the present study, however, a complete inversion of the stereoselectivity was observed merely by changing these two parameters. This warranted further systematic study in order to attain an understanding of the factors responsible for the change in stereoselectivity.

Table 1. Stereoselective Enolboration of Selected $CH_3CH_2CONR'_2$ with Chx_2BI/Et_3N under Different Experimental Conditions

		T (°C)		aldol (%)		
NR'_2	solvent	enol.[a]	aldol.[b]	syn	anti	yield (%)[c]
$N(CH_2)_5$	CCl_4	0	0	<3	>97	95
	hexane	0	−78	>97	<3	93
NMe_2	CCl_4	0	0	5	95	96
	hexane	0	−78	>97	<3	96
NEt_2	CCl_4	0	0	5	95	94
	hexane	0	−78	88	12	93
N-*i*-Pr_2	CCl_4	0	0	<3	>97	70
	hexane	0	−78	46	54	68

[a] Enolization for 2 h. [b] Aldolization with PhCHO for 3 h. [c] Based on ^1H NMR.

Scheme 2



Effect of Solvent. The enolization of *N,N*-dimethylpropionamide, $CH_3CH_2CONMe_2$, with Chx_2BI/Et_3N was selected as a model reaction to investigate the effect of solvent on stereochemistry. Reactions were carried out in various solvents, such as aliphatic and aromatic hydrocarbons and chlorinated aliphatic solvents. Ether solvents were avoided since the R_2BI reagents are known to cleave them.[12b]

The results in Table 2 suggest that aliphatic and alicyclic hydrocarbon solvents favor formation of syn aldols, while the other solvents examined favor formation of anti aldols. This unusual solvent effect could not be attributed to their polarity differences.

Special Experiments. In the present study, on the basis of excellent yield and selectivity, an optimized procedure involving dropwise addition of amine to a mixture of Chx_2BI and amide was employed. When both Chx_2BI and the amide was mixed in hexane and in other aliphatic or alicyclic hydrocarbon solvents, a pale yellow solid was observed, probably due to complexation or cordination. However, no solid was observed in CCl_4 and in the other aromatic and chlorinated aliphatic solvents examined. When the amine was added to this mixture, enolization took place.

Our original interpretation was that the physical nature (solid or liquid) of the Chx_2BI and amide mixture might be responsible for the observed unusual stereoselectivity. Therefore, a study was carried out under selected experimental conditions, and the results are presented in Table 3.

The pale yellow solid, obtained by mixing both Chx_2BI and $CH_3CH_2CONMe_2$ in hexane at 0 °C, was suspended in CCl_4 (only sparingly soluble) after removal of hexane, and then the enolization was carried out by adding Et_3N at 0 °C. The aldolization of this enolate in CCl_4 with PhCHO gave the anti aldol predominantly

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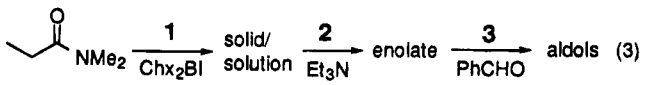
Table 2. Systematic Study of the Enolboration of $CH_3CH_2CONMe_2$ with Chx_2BI/Et_3N in Selected Solvents and Temperatures

	T (°C)		aldol (%)		
solvent	enol.[a]	aldol.[b]	syn	anti	yield (%)[c]
hexane	0	0	60	40	95
	0	25	58	42	94
	0	−78	>97	<3	93
pentane	0	0	80	20	95
	0	−78	>97	<3	94
methylcyclohexane	0	0	73	27	94
	0	−78	>97	<3	95
octane	0	0	89	11	92
toluene	0	0	11	89	92
	0	−78	>97	<3	90
benzene	5	5	22	78	93
CH_2Cl_2	0	0	23	77	90
	0	−78	29	71	91
$CHCl_3$	0	0	16	84	94
$CHCl_3/CH_2Cl_2$ (1:3)	0	0	14	86	89
	0	−78	21	79	84
$CHCl_3/CH_2Cl_2$ (9:1)	0	0	17	83	87
	0	−78	22	78	85
CCl_4	0	0	5	95	96
	0	25	17	83	95
	25	0	12	88	92
	25	25	17	83	93

[a] Enolization for 2 h. [b] Aldolization with PhCHO for 3 h. [c] Based on ^1H NMR.

Table 3. Results of Special Experiments on Tertiary Amides[a,b]



	solvent[c,d]			aldol (%)		
amide	1	2	3	syn	anti	yield (%)[e]
$CH_3CH_2CONMe_2$	hexane	hexane	hexane	60	40	95
	CCl_4	CCl_4	CCl_4	5	95	96
	hexane	CCl_4	CCl_4	7	93	94
	hexane	hexane	CCl_4	8	92	95
	$CHCl_3$	$CHCl_3$	$CHCl_3$	16	84	95
	hexane	$CHCl_3$	$CHCl_3$	20	80	85
	hexane	hexane	$CHCl_3$	28	72	87
	CCl_4	hexane	hexane	5	95	92
	CCl_4	CCl_4	hexane	6	94	90
	C/H[f]	C/H	C/H	6	94	92
	hexane	hexane	C/H	20	80	86
$CH_3CH_2CONEt_2$	hexane	hexane	hexane	66	34	93
	CCl_4	CCl_4	CCl_4	5	95	94
	hexane	CCl_4	CCl_4	6	94	95
	hexane	hexane	CCl_4	11	89	90

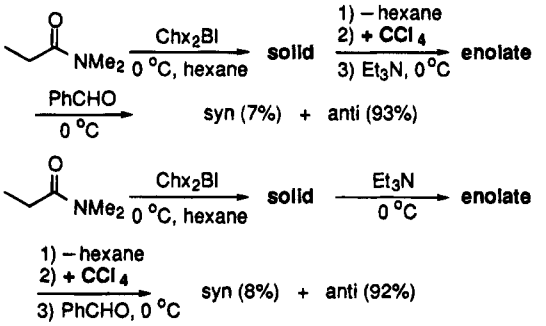
[a] Enolization at 0 °C for 2 h. [b] Aldolization with PhCHO at 0 °C for 3 h. [c] Solvent was removed by evaporation (15–20 mm). [d] Refer to eq 3 above. [e] Based on ^1H NMR. [f] C/H = CCl_4/hexane (1:1).

(Scheme 3). The enol borinate generated in hexane also gave the anti aldol as the major product when the subsequent aldolization was carried out in CCl_4.

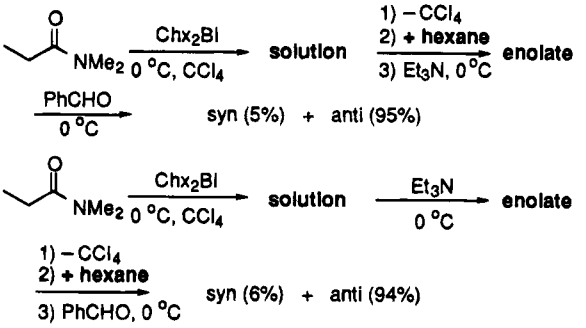
These results clearly suggest that the nature of solvent influences the aldol stereoselectivity greatly. Similar experiments with $CHCl_3$ in place of CCl_4 (Table 3) also corroborate the important effect of solvent.

A pale yellow solid was also obtained when CCl_4 was removed by evaporation from the homogeneous mixture of Chx_2BI and amide in CCl_4 at 0 °C. This solid was only sparingly soluble in hexane. When both the enolization and the aldolization were carried out in hexane, surprisingly, only the anti aldol was obtained as the major product (Scheme 4). The preformed enol borinate in CCl_4

Scheme 3



Scheme 4



also gave the anti aldol predominantly when the subsequent aldolization was carried out in hexane.

A mixture of CCl_4 and hexane also yielded the anti aldol as the major product. All these results infer that the use of CCl_4 in any one of the steps favors the formation of the anti aldol. The results obtained with a different substrate, $CH_3CH_2CONEt_2$, also gave similar conclusions.

Effect of Aldolization Temperature. Our earlier systematic study in the enolboration of ketones with Chx_2BCl/Et_3N showed that the aldolization temperature does not have much effect on the stereochemistry.[6c] However, the present study with tertiary amides reveals a considerable influence of temperature on stereochemistry. A systematic study was therefore carried out at different temperatures, and the results are included in Table 2.

In the cases of aliphatic and alicyclic solvents, the syn aldol was obtained either predominantly or essentially exclusively at −78 °C. However, with polar solvents, such as CH_2Cl_2, CH_3CH_2I, and $CH_3CH_2CH_2I$, the syn selectivity is not good even at −78 °C. Use of a mixture of $CHCl_3$ and CH_2Cl_2 (9:1) also gave only the anti aldol as the major product. We tried to use ethyl and *n*-propyl iodides as solvents which would be liquid at −78 °C. But the yields of enolates and aldols were quite low, 10–18%. Possibly the Chx_2BI catalyzes the reaction of the amine with these solvents to form the corresponding quarternary ammonium salts. The results clearly suggest that the effect of solvent controls the stereochemistry more than that of the aldolization temperature. Therefore, the syn aldol was favored in nonpolar aliphatic and alicyclic hydrocarbon solvents at −78 °C and the anti aldol was favored in more polar solvents examined at 0 °C or at room temperature. A similar unusual effect of aldolization temperature on stereochemistry has also been reported for the magnesium enolate derived from tertiary thioamides.[13] The syn aldol was obtained predominantly at −78 °C and the anti aldol exclusively at room tempera-

Table 4. Relationship between the Enolate and the Aldolate Geometry in the Enolboration of $PhCH_2CONMe_2$ with Chx_2BI/Et_3N

enol.[a]		aldol.[b]		enolate (%)[c]		aldol (%)		
solvent	T (°C)	solvent	T (°C)	Z	E	syn	anti	yield[d]
CCl_4	0	CCl_4	0	23	77	44	56	95
$CDCl_3$	0	$CDCl_3$	0	<3[e]	>97	77	23	93
hexane[f,g]	0	CCl_4	0	<3	>97	47	53	92
hexane[g]	0	hexane	0	<3	>97	84	16	96
hexane[g]	0	hexane	−78	<3	>97	90	10	95

[a] Enolization for 2 h. [b] Aldolization with PhCHO for 3 h. [c] The *Z* enolate appears at δ 4.89 ppm (s) and the *E* enolate appears at δ 4.70 (s). [d] Based on ^1H NMR. [e] In cases where the spectrum shows only one major isomer, we have indicated the minor isomer to be <3% since such small peaks may be lost in the background. [f] Solvent hexane was removed after enolization by evaporation. [g] The ^1H NMR was recorded in CCl_4 or in $CDCl_3$ after removing hexane.

ture both in THF.[13] Toluene is a unique solvent, favoring the preferential formation of the anti aldol at 0 °C and the syn aldol at −78 °C. However, such a selectivity was not observed with other substrates under similar conditions.

Relationship between the Enolate and the Aldolate Stereochemistry. Koster has prepared various enol borinates and demonstrated that *Z* enol borinates give syn aldols and *E* enol borinates give anti aldols stereoselectivity (Scheme 1).[4] Evans has clearly documented the exceptional stereoselectivity of enol borinates and proposed a six membered transition state[8] on the basis of the Zimmerman and Traxler model.[14a] We have also established the stereoselectivity of enol borinates of various ketones and other carbonyl derivatives for aldol reactions.[5,6] Under all experimental conditions, *Z* enol borinates give syn aldols and *E* enol borinates give anti aldols essentially exclusively. However, in the present study, we have observed for the first time an important effect of solvent and temperature on aldol stereochemistry for tertiary amides.

Generally, both *Z* and *E* enol borinates possess essentially the same chemical shift values and, therefore, the direct determination of the *Z*/*E* ratio by ^1H NMR is very difficult. Therefore, this has been indirectly obtained from the corresponding syn/anti ratio of the aldol products.[5-10] The enol borinates derived from aromatic carbonyl compounds, however, have different chemical shift values for *Z* and *E* isomers.[5,6] Therefore, it was decided to determine the *Z*/*E* ratios directly by ^1H NMR from an aromatic tertiary amide and then to relate to the syn/anti ratios to find out the stereospecificity of boron enolates of tertiary amides. The *Z* enolate obtained from $PhCH_2CONMe_2$ appears at δ 4.89 and the *E* enolate appears at δ 4.70. The enolate geometry was assigned on the basis of our earlier anology that *Z* enol borinates appear downfield as compared to the isomeric *E* enol borinates.[5,6]

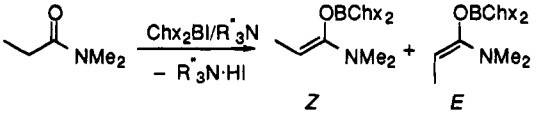
The results presented in Table 4 suggest that a mixture of syn and anti aldol was obtained from the *E* enolate. This is quite different from the behavior observed for the boron enolates.[5-10] The unusual effects of solvent and temperature on the stereochemistry raise a question about the validity of the well-established *Z* to syn and *E* to anti relationship previously observed in these studies. This suggests that there may be an isomerization of enol borinates under different reaction conditions or a different transition state for aldol reaction, such as the open-chain transition state as proposed by Heathcock and his co-workers[14b] or some other factor not yet established. This direct comparison of the enolate and the aldol stereochemistry also confirms the considerable effect of solvent on the aldol stereoselection. This study suggests that the *Z*/*E* ratios cannot be determined from the corresponding syn/anti ratios in the case of tertiary amides.

Table 5. Effect of Steric Requirements of Amine in the Enolboration of $CH_3CH_2CONMe_2$ with Chx_2BI under Different Experimental Conditions

		T (°C)		aldol (%)		
amine	solvent	enol.[a]	aldol.[b]	syn	anti	yield (%)[c]
Me_2EtN	CCl_4	0	0	8	92	95
	hexane	0	0	65	35	96
		0	−78	>97	<3	95
Et_2MeN	CCl_4	0	0	5	95	96
	hexane	0	0	58	42	95
		0	−78	>97	<3	94
Et_3N	CCl_4	0	0	5	95	96
	hexane	0	0	60	40	95
		0	−78	>97	<3	96
Et_2-*i*-PrN	CCl_4	0	0	8	92	70
	hexane	0	0	65	35	94
		0	−78	>97	<3	96
i-Pr_2EtN	CCl_4	0	0	19	81	85
	hexane	0	0	22	78	80
		0	−78	34	66	83
i-Pr_3N[d]	CCl_4	0	0	–	–	–
	hexane	0	0	–	–	–
		0	−78	–	–	–

[a] Enolization for 2 h. [b] Aldolization with PhCHO for 3 h. [c] Based on ^1H NMR. [d] No reaction even at 25 °C.

Effect of Steric Requirements of Amine. To understand the effect of amine on the stereochemistry and also to establish the most suitable amines for the quantitative and stereoselective enolboration, a systematic investigation of the enolboration of $CH_3CH_2CONMe_2$ was carried out with representative tertiary amines of variable steric requirements (eq 4).



(4)

R^*_3N = Me_2EtN, Et_2MeN, Et_3N, Et_2-*i*-PrN, *i*-Pr_2EtN, *i*-Pr_3N

It was observed in the enolboration of esters with Chx_2BI that the smaller amines, such as Me_2EtN and Et_2MeN, coordinate strongly with this reagent and, therefore, are totally ineffective for enolization.[12b] In the present study, however, the reverse addition achieved a quantitative enolboration of tertiary amides even with these smaller amines.

The results in Table 5 indicate an interesting relationship between the steric requirements of amine and the stereochemistry. All the amines examined, except for the more bulky *i*-Pr_2EtN, gave anti aldols in CCl_4 at 0 °C and syn aldols in hexane at −78 °C as the major product. However, *i*-Pr_2EtN favored either exclusive or predominant formation of the anti aldol under all experimental conditions. As observed in the enolboration of ketones,[6c] the highly hindered *i*-Pr_3N could not achieve enolization

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Table 6. Stereoselective Enolboration of Representative $CH_3CH_2CONR'_2$ with Chx_2BI/i-Pr_2EtN under Different Experimental Conditions

		T (°C)		aldol (%)		
NR'_2	solvent	enol.[a]	aldol.[b]	syn	anti	yield (%)[c]
$N(CH_2)_5$	CCl_4	0	0	3	97	90
	hexane	0	−78	56	44	89
NMe_2	CCl_4	0	0	19	81	94
	hexane	0	−78	34	66	90
NEt_2	CCl_4	0	0	4	96	93
	hexane	0	−78	38	62	92
N-i-Pr_2	CCl_4	0	0	<3	>97	60
	hexane	0	−78	22	78	56

[a] Enolization for 2 h. [b] Aldolization with PhCHO for 3 h. [c] Based on ^1H NMR.

even at 25 °C. Enolborations were also repeated for the other representative tertiary amides with Chx_2BI in the presence of i-Pr_2EtN, and the results are summarized in Table 6. These results suggest that i-Pr_2EtN favors formation of anti aldols both in CCl_4 and in hexane from the various substrates examined. This study also establishes many suitable amines for the successful enolboration of tertiary amides with the highly reactive Chx_2BI.

Conclusions

Dicyclohexyliodoborane is the first, successful, highly stereoselective reagent for the enolboration of tertiary amides. A systematic study of the enolboration of representative *N,N*-dialkylpropionamides ($CH_3CH_2CONR'_2$) with Chx_2BI in the presence of various tertiary amines reveals an unusual aldol stereoselectivity in different solvents and at different aldolization temperatures. Both the nature of solvent and the aldolization temperature influence the stereochemistry of enolboration, with the solvent effect being greater than that of the temperature. Aliphatic and alicyclic hydrocarbon solvents favor formation of syn aldols at −78 °C, whereas most of the other solvents examined, such as aromatic and chlorinated aliphatic solvents, favor formation of anti aldols at 0 or 25 °C. The remarkable effects of both temperature and solvent in the case of tertiary amides raise a question about the validity of the previously assumed constancy of the *Z* to syn and *E* to anti relationship, suggesting either a possible isomerization of enol borinates with temperature or a different aldolization transition state with different solvent. While the effect of steric requirements of the dialkylamino group of the tertiary amides does not contribute significantly to the stereochemistry, that of the amine exerts a considerable influence. The present study also establishes a simple procedure for the stereoselective synthesis of either syn or anti aldols from representative tertiary amides merely by changing the solvent and the aldolization temperature. The remarkable reactivity, impressive stereoselectivity, ease of preparation and handling, and the greater stability combine to make Chx_2BI a highly versatile reagent for the stereoselective enolboration of tertiary amides.

Experimental Section

Materials. All glassware was thoroughly dried in an air oven, cooled, and assembled under nitrogen for the experiments. Degassed, anhyd solvents were used in the present study. All tertiary amides, except for *N,N*-diisopropylpropionamide and *N*-propionylpiperidine, were commercial products of the highest purity available. A simple method for the preparation of these two amides is given below. All amines, except for Et_2-i-PrN and i-Pr_3N, were purchased commercially, distilled over CaH_2, and used. The procedures for the preparation of Et_2-i-PrN and i-Pr_3N are reported elsewhere.[6c,15] The preparation of dicyclohexyliodoborane is described in our earlier paper.[12b] The special experimental techniques used in handling air- and moisture-sensitive compounds have been reported elsewhere.[16] ^1H, ^{11}B, and ^{13}C NMR spectra were recorded on a 300-MHz instrument. The chemical shift values (δ) for ^1H and ^{13}C NMR are relative to TMS and that of ^{11}B NMR are relative to BF_3·OEt_2. All of the following enolization and aldolization experiments were conducted in a 100-mL round-bottom flask capped with rubber septum, a magnetic stirring bar, and a connecting tube attached to a mercury bubbler under a nitrogen atmosphere.

Synthesis of Amides. Both *N,N*-diisopropylpropionamide and *N*-propionylpiperidine were prepared from the commercially available propionyl chloride and the required amine using the following general procedure. To a mixture of Et_3N (62 mL, 445 mmol) and the amine (i-Pr_2NH or piperidine, 445 mmol) in ether (150 mL) at 0 °C was added propionyl chloride slowly while stirring. A concurrent formation and precipitation of Et_3N·HCl suggested an instantaneous reaction. The reaction mixture was stirred at 0 °C for 1 h and then at 25 °C for 2−3 h. The white precipitate was filtered off, and the ether solution containing the product was washed with water, aqueous K_2CO_3 solution, and finally with water. The solution was then dried over anhyd Na_2SO_4, and the ether was removed by distillation. The concentrated solution was then distilled to get >99% GC pure *N,N*-diisopropylpropionamide (70% yield, bp 205−206 °C) or *N*-propionylpiperidine (65% yield, bp 238−240 °C). ^1H and ^{13}C NMR spectra confirmed the structures.

General Procedure for the Enolization of Tertiary Amides with Chx_2BI/R''_3N in CCl_4. To a stirred solution of Chx_2BI (5.00 mmol) in CCl_4 (17.0 mL) at 0 °C was added the amide (5.00 mmol) dropwise. To this homogeneous solution at 0 °C was added R''_3N (5.00 mmol) dropwise, and the enolate was generated rapidly with concurrent formation and precipitation of R''_3N·HI. An internal standard, benzene (0.50 mL, 1.00 M in CCl_4, 0.50 mmol), was added for quantification of the enolate by ^1H NMR analysis, except for $PhCH_2CONMe_2$, where the aromatic protons were used as the standard. The reaction mixture was stirred at 0 °C for 2 h and then transferred into a centrifuge vial using a double-ended needle (18 gauge). Centrifugation resulted in the separation of the enol borinate solution from the precipitated R''_3N·HI. In representative cases, the solid R''_3N·HI has been collected, washed, dried, and weighed. The yields were comparable with that determined directly by ^1H NMR. The enol borinate solution was then transferred into an NMR tube using a double-ended needle. The ^1H NMR analysis gave the extent of enolboration and ^{11}B NMR (broad, around 50−56 ppm) also confirmed the formation of enol borinates. The ^1H NMR data of the olefinic protons of the representative enol borinates were reported in our earlier communication.[12a]

General Procedure for the Enolization of Tertiary Amides with Chx_2BI/R''_3N in Hexane. To a stirred solution of Chx_2BI (5.00 mmol) in hexane (17.0 mL) at 0 °C was added the amide (5.00 mmol) dropwise. A pale yellow solid was obtained immediately. To this heterogeneous mixture at 0 °C was added R''_3N (5.00 mmol) dropwise. The solid dissolved as the enolization proceeded, generating the enol borinate with concurrent formation and precipitation of R''_3N·HI. The reaction mixture was stirred at 0 °C for 2 h and then transferred into a centrifuge vial using a double-ended needle (18 gauge). Centrifugation resulted in the separation of the enol borinate solution from the precipitated R''_3N·HI. In representative cases, the solid R''_3N·HI was collected, washed, dried, and weighed. Essentially quantitative yields were obtained. The enol borinate solution was then transferred into an NMR tube

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using a double-ended needle. ^{11}B NMR (broad, around 50–56 ppm) confirmed the formation of enol borinates.

General Procedure for the Enolization of $CH_3CH_2CONMe_2$ with Chx_2BI/Et_3N in Toluene, Benzene, CH_2Cl_2, $CHCl_3$, CH_3CH_2I, and $CH_3CH_2CH_2I$. To a stirred solution of Chx_2BI (5.00 mmol) in the required solvent (17.0 mL) at 0 °C (except for benzene, 5 °C) was added $CH_3CH_2CONMe_2$ (5.00 mmol) dropwise. To this homogeneous solution at 0 °C was added Et_3N (5.00 mmol) dropwise. The reaction mixture was stirred at the enolization temperature (Table 2) for 2 h, and then the enol borinate solution was transferred into an NMR tube using a double-ended needle. ^{11}B NMR (broad, around 50–56 ppm) confirmed the formation of enol borinates.

General Procedure for the Enolization of $CH_3CH_2CONMe_2$ with Chx_2BI/Et_3N in Pentane, Methylcyclohexane, and Octane. To a stirred solution of Chx_2BI (5.00 mmol) in the required solvent (17.0 mL) at 0 °C was added $CH_3CH_2CONMe_2$ (5.00 mmol) dropwise. A pale yellow solid was obtained immediately. To this heterogeneous mixture at 0 °C was added Et_3N (5.00 mmol) dropwise. The solid dissolved, generating the enol borinate with concurrent formation and precipitation of $Et_3N{\cdot}HI$. The reaction mixture was stirred at 0 °C for 2 h and then transferred into a centrifuge vial using a double-ended needle (18 gauge). Centrifugation resulted in the separation of the enol borinate solution from the precipitated $Et_3N{\cdot}HI$. The solution was then transferred into an NMR tube using a double-ended needle. ^{11}B NMR (broad, around 50–56 ppm) confirmed the formation of enol borinates.

General Procedure for the Aldolization (at 0 °C) of the Enolates, Generated with Chx_2BI/R''_3N, with PhCHO. To a solution of the enolate generated from 5.00 mmol of the amide using Chx_2BI/R''_3N in the required solvent as described above was added PhCHO (5.00 mmol) dropwise at 0 °C. The reaction mixture was stirred at 0 °C for 3 h, and then 10 mL of methanol was added. Consequently, 2.50 mL of H_2O_2 (30%) was also added dropwise at 0 °C. A pink color was observed, attributed to the formation of iodine. It was then stirred at 25 °C for 3 h. The solvent and methanol were then removed by a water aspirator (15–20 mm), and the reaction mixture was extracted with ether. The dark-colored ether solution containing iodine was washed with dilute sodium thiosulfate solution and then with water. The colorless ether solution was dried over anhyd Na_2SO_4, the solvent was evaporated, and the products were analyzed as such by ^1H NMR to determine the syn/anti ratio.

General Procedure for the Aldolization (at −78 °C) of the Enolates, Generated with Chx_2BI/R''_3N, with PhCHO. To a solution of the enolate generated from 5.00 mmol of the amide using Chx_2BI/R''_3N in the required solvent as described above was added PhCHO (5.00 mmol) dropwise at −78 °C. The reaction mixture was stirred at this temperature for 3 h, and then 10 mL of methanol was added. Consequently, 2.50 mL of H_2O_2 (30%) was also added dropwise at −78 °C. It was then stirred at 25 °C for 3 h. The usual pink color was observed. The solvent and methanol were removed by a water aspirator (15–20 mm), and the reaction mixture was extracted with ether. The dark-colored ether solution was washed with dilute sodium thiosulfate solution and then with water. The colorless ether solution was dried over anhyd Na_2SO_4, the solvent was evaporated, and the products were analyzed as such by ^1H NMR to determine the syn/anti ratio.

General Procedure for Special Experiments. A representative procedure is given as follows. To a stirred solution of Chx_2BI (5.00 mmol) in hexane (17.0 mL) at 0 °C was added $CH_3CH_2CONMe_2$ (5.00 mmol) dropwise. A pale yellow solid was obtained immediately. Hexane was then removed by evaporation using a water aspirator (15–20 mm). The solid obtained was suspended in CCl_4 (17.0 mL) at 0 °C, and Et_3N (5.00 mmol) was added dropwise. The solid dissolved as the enolization proceeded, generating the enol borinate with concurrent formation and precipitation of $Et_3N{\cdot}HI$. The reaction mixture was stirred at 0 °C for 2 h. To this enolate solution was added PhCHO (5.00 mmol) dropwise at 0 °C. The reaction mixture was stirred at this temperature for 3 h, and then 10 mL of methanol was added. Consequently, 2.5 mL of H_2O_2 (30%) was also added dropwise at 0 °C. It was then stirred at 25 °C for 3 h. The solvent and methanol were then removed by a water aspirator (15–20 mm), and the reaction mixture was extracted with ether. The dark-colored ether solution containing iodine was washed with dilute sodium thiosulfate solution and then with water. The colorless ether solution was dried over anhyd Na_2SO_4, the solvent was evaporated, and the products were analyzed as such by ^1H NMR.

General Procedure with Two Different Solvents. A representative procedure is given as follows. The enolate was generated in hexane (17.0 mL) at 0 °C from 5.00 mmol of $CH_3CH_2CONMe_2$ with Chx_2BI/Et_3N as already described. The solvent hexane was then removed by evaporation using a water aspirator (15–20 mm), and the product enolate mixture was suspended in CCl_4 (17.0 mL). To this enolate solution was added PhCHO (5.00 mmol) dropwise at 0 °C. The reaction mixture was stirred at this temperature for 3 h, and then 10 mL of methanol was added. Consequently, 2.5 mL of H_2O_2 (30%) was also added dropwise at 0 °C. It was then stirred at 25 °C for 3 h. The solvent and methanol were then removed by a water aspirator (15–20 mm), and the reaction mixture was extracted with ether. The dark-colored ether solution containing iodine was washed with dilute sodium thiosulfate solution and then with water. The colorless ether solution was dried over anhyd Na_2SO_4, the solvent was evaporated, and the products were analyzed as such by ^1H NMR.

Optimized Procedure To Achieve Syn Aldols. To a solution of the enolate generated from 20.00 mmol of the amide using Chx_2BI/Et_3N (20.00 mmol each) in hexane (70 mL) at 0 °C (3 h) as described above was added PhCHO (20.00 mmol) dropwise at −78 °C. The reaction mixture was stirred at this temperature for 3 h, and then 20 mL of methanol was added. Consequently, 8.0 mL of H_2O_2 (30%) was also added dropwise at −78 °C. It was then stirred at 25 °C for 3 h. The solvent and methanol were then removed by a water aspirator (15–20 mm), and the reaction mixture was extracted with ether. The dark-colored ether solution containing iodine was washed with a dilute sodium thiosulfate solution and then with water. The colorless ether solution was dried over anhyd Na_2SO_4, the solvent was evaporated, and the products were analyzed as such by ^1H NMR. In representative cases ($CH_3CH_2CONMe_2$ and $CH_3CH_2CONEt_2$), the aldol products were isolated by chromatography (hexane/ether, 4:1). The spectral and other analytical data are given below.

***syn*-PhCH(OH)CH(Me)CONMe$_2$**: isolated yield 84%, mp 92 °C (lit.[17a] mp 91.1–92 °C); ^1H NMR ($CDCl_3/D_2O$) δ 1.03 (d, 3 H, J = 7.11), 2.86 (qd, 1 H, J = 7.07, 2.31), 2.98 (s, 3 H), 3.02 (s, 3 H), 5.08 (d, 1 H, J = 2.25), 7.10–7.30 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 9.464, 35.428, 37.343, 41.510, 73.151, 126.014, 127.074, 128.109, 141.731, 177.442; MS m/z 207 (M^+) 190, 107, 101, 81, 72. Anal. Calcd for $C_{12}H_{17}NO_2$: C, 69.53; H, 8.27; N, 6.76. Found: C, 69.80; H, 8.54; N, 6.72.

***syn*-PhCH(OH)CH(Me)CONEt$_2$**: isolated yield 72%, mp 72 °C (lit.[17b] mp 72–73 °C); ^1H NMR ($CDCl_3/D_2O$) δ 1.05 (d, 3 H, J = 7.20), 1.12 (t, 3 H, J = 7.05), 1.20 (t, 3 H, J = 7.05), 2.78 (qd, 1 H, J = 6.99, 2.70), 3.28 (m, 3 H), 3.49 (m, 1 H), 5.05 (d, 1 H, J = 2.4), 7.20–7.40 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 10.268, 12.969, 14.861, 40.319, 41.481, 42.143, 73.486, 126.034, 127.116, 128.114, 141.879, 176.774. MS m/z 235 (M^+) 220, 129, 107, 100, 77, 72, 58. Anal. Calcd for $C_{14}H_{21}NO_2$: C, 71.45; H, 8.99; N, 5.95. Found: C, 71.13; H, 9.26; N, 5.90.

The ^1H NMR data of the PhCHO aldol products (benzylic proton) of the other tertiary amides examined are given in Table 7.

Optimized Procedure To Achieve Anti Aldols. To a solution of the enolate generated from 20.00 mmol of the amide using Chx_2BI/Et_3N (20.00 mmol each) in CCl_4 (70 mL) at 0 °C (3 h) as described above was added PhCHO (20.00 mmol) dropwise at 0 °C. The reaction mixture was stirred at 0 °C for 3 h, and then 20 mL of methanol was added. Consequently, 8.0 mL of H_2O_2 (30%) was also added dropwise at 0 °C. It was then stirred at 25 °C for 3 h. The solvent and methanol

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Table 7. ^{1}H NMR Data of the Carbinol Protons of the Syn and Anti Aldols

amide	^{1}H NMR[a] (δ)	
	syn	anti
$CH_3CH_2CON(CH_2)_5$	5.10 (d, J = 2.52)	4.77 (d, J = 5.61)
$CH_3CH_2CONMe_2$	5.06 (d, J = 2.94)	4.76 (d, J = 6.24)
$CH_3CH_2CONEt_2$	5.04 (d, J = 2.76)	4.75 (d, J = 4.74)
$CH_3CH_2CONi\text{-}Pr_2$	5.05 (d, J = 2.73)	4.73 (d, J = 4.59)
$PhCH_2CONMe_2$	5.41 (d, J = 3.27)	5.10 (d, J = 8.10)
N-methyl-2-piperidone	5.29 (d, J = 3.48)	4.69 (d, J = 9.60)

[a] Corresponds to the benzylic proton of the benzaldehyde aldol products. J values are in hertz.

were then removed by a water aspirator (15–20 mm), and the reaction mixture was extracted with ether. The dark-colored ether solution containing iodine was washed with dilute sodium thiosulfate solution and then with water. The colorless ether solution was dried over anhyd Na_2SO_4, the solvent was evaporated, and the products were analyzed as such by ^{1}H NMR. In representative cases ($CH_3CH_2CONMe_2$ and $CH_3CH_2CONEt_2$), the aldol products were isolated by chromatography (hexane/ether, 4:1). The spectral and other analytical data are given below.

***anti*-PhCH(OH)CH(Me)CONMe$_2$**: isolated yield 82%, mp 84 °C; ^{1}H NMR ($CDCl_3/D_2O$) δ 1.18 (d, 3 H, J = 7.02), 2.84 (s, 3 H), 2.88 (s, 3 H), 3.04 (m, 1 H), 4.77 (d, 1 H, J = 5.76), 7.20–7.40 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 15.310, 35.378, 37.197, 42.607, 76.700, 126.108, 127.483, 128.276, 143.003, 175.795; MS m/z 207 (M^+) 190, 107, 101, 81, 72. Anal. Calcd for $C_{12}H_{17}NO_2$: C, 69.53; H, 8.27; N, 6.76. Found: C, 69.42; H, 8.48; N, 6.75.

***anti*-PhCH(OH)CH(Me)CONEt$_2$**: isolated yield 80%, mp 55 °C (lit.[17c] mp 56 °C). ^{1}H NMR ($CDCl_3/D_2O$) δ 0.91 (t, 3 H, J = 7.20), 1.00 (t, 3 H, J = 7.05), 1.28 (d, 3 H, J = 6.90), 2.90 (m, 1 H), 3.02 (qd, 2 H, J = 7.8, 9.69), 3.24 (m, 2 H), 4.75 (d, 1 H, J = 4.50), 7.20–7.35 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 12.862, 14.331, 16269, 40.443, 42.098, 42.196, 76.732, 125.949, 127.342, 128.204, 143.495, 175.354; MS m/z 235 (M^+) 220, 129, 107, 100, 77, 72, 58. Anal. Calcd for $C_{14}H_{21}NO_2$: C, 71.45; H, 8.99; N, 5.95. Found: C, 71.22; H, 9.16; N, 5.75.

Acknowledgment. We gratefully acknowledge financial support from the United States Office of Naval Research, which made this research possible. We also thank Dr. S. Narasimhan and Dr. A. Mukhopadhyay for a sample of triisopropylamine.

Supplementary Material Available: ^{1}H and ^{13}C NMR spectra of the isolated syn and anti aldols of $CH_3CH_2CONMe_2$ and $CH_3CH_2CONEt_2$, ^{1}H NMR spectra of enol borinates from $PhCH_2CONMe_2$, and representative ^{1}H NMR spectra of the PhCHO aldol products of the enol borinates representing each study (36 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.