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Desulfurization with Nickel and Cobalt Boride: Scope, Selectivity, Stereochemistry, and Deuterium-Labeling Studies

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A variety of organosulfur compounds containing alkylthio and arylthio groups underwent reductive desulfurization under notably mild conditions when treated with nickel boride, generated in situ from nickel chloride hexahydrate and sodium borohydride in methanol–THF (3:1). Phenyl, chloro, and ester groups are not reduced under these conditions, while iodo, bromo, nitrile, aldehyde, ketone, cyclopropane, and olefinic functions are reduced either completely or partially. Deuterium-labeling studies indicate that the hydrogen that is incorporated into the product originates from both the sodium borohydride and the protic solvent, suggesting the intermediacy of dihydrogen. The epimers 3α- and 3β-(phenylthio)cholestane afforded 3α- and 3β-deuteriocholestane, respectively, demonstrating that the reaction proceeds with retention of configuration. The method may thus be employed for the stereospecific preparation of deuterated products from organosulfur compounds. Arguments are presented in support of a tentative mechanism involving an oxidative addition–reductive elimination sequence via a nickel hydride intermediate.

Nickel and cobalt boride were first reported by Schlesinger and co-workers[1] in 1953 and have since been employed as reagents and catalysts in a number of important processes.[2] The borides are easily prepared by the reduction of Ni(II) or Co(II) salts with sodium borohydride, usually in alcohol or aqueous solutions, from which they precipitate as fine black solids, accompanied by the vigorous evolution of hydrogen. The stoichiometry for the formation of nickel boride under these conditions is shown in eq 1. Both nickel and cobalt borides catalyze

$$8NaBH_4 + 4NiCl_2 + 18ROH \xrightarrow[R = H, Me, \text{ or } Et]{} 2Ni_2B + 6B(OR)_3 + 8NaCl + 25H_2 \quad (1)$$

the further reaction of sodium borohydride with protic solvents according to eq 2.[1]

$$NaBH_4 + ROH \xrightarrow{Ni_2B} NaB(OR)H_3 + H_2 \xrightarrow{\text{etc.}} \quad (2)$$

Nickel boride also catalyzes the hydrogenation of olefins and acetylenes,[3] and both borides act as reducing agents toward a variety of functional groups. Although their detailed structures are unknown, their elemental compositions are consistent with the formulas Ni_2B and Co_2B, respectively, and these species contain hydrogen that is gradually released upon heating.[4] Since nickel and cobalt borides are easy to prepare and convenient to handle, there is continuing interest in their properties and applications.

Reductive desulfurization is of importance in organic synthesis, where sulfur functionalities that are employed to manipulate the structure of a substrate must usually be removed in the final step. Furthermore, desulfurization processes are crucial to the fuel-processing industry, since the combustion of sulfur-containing fuels results in pollution from the resulting release of sulfur dioxide. The use of nickel boride as a desulfurization reagent (eq 3) was

$$RSR' \xrightarrow[(NiX_2 + NaBH_4)]{Ni_2B} RH + R'H \quad (3)$$

first reported by Truce and co-workers,[5] followed by several other groups.[6] However, these earlier reports were generally confined to a relatively narrow range of substrates and sometimes employed conditions that did not produce high yields. We recently demonstrated that nickel boride can be used in a convenient and mild procedure for the desulfurization of benzo- and dibenzothiophenes,[7] as well as in a variety of deselenizations.[8,9] To date, little is known about the scope, chemoselectivity, stereochemistry, or mechanism of nickel boride-mediated desulfurizations, and the use of cobalt boride for this purpose has not, to our knowledge, yet been reported. As part of our continuing studies in this area, we now describe the results of an investigation with a series of alkylthio and arylthio compounds in order to address the above questions.

Results and Discussion

Optimization, Scope, and Selectivity. The choice of nickel chloride hexahydrate ($NiCl_2{\cdot}6H_2O$) as the nickel(II) salt and methanol–THF (3:1) as the solvent was based

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[†] Undergraduate Summer Research Assistant (1992).

(1) Schlesinger, H. I.; Brown, H. C.; Finholt, A. E.; Gilbreath, J. R.; Hoekstra, H. R.; Hyde, E. K. *J. Am. Chem. Soc.* **1953**, *75*, 215.

(2) For a review, see: Ganem, B.; Osby, J. O. *Chem. Rev.* **1986**, *86*, 763.

(3) Brown, C. A.; Ahuja, V. K. *J. Org. Chem.* **1973**, *38*, 2226.

(4) Maybury, P. C.; Mitchell, R. W.; Hawthorne, M. F. *J. Chem. Soc., Chem. Commun.* **1974**, 534.

(5) (a) Truce, W. E.; Roberts, F. E. *J. Org. Chem.* **1963**, *28*, 961. (b) Truce, W. E.; Perry, F. M. *J. Org. Chem.* **1965**, *30*, 1316.

(6) (a) Clark, J.; Grantham, R. K.; Lydiate, J. *J. Chem. Soc. C* **1968**, 1122. (b) Schut, J.; Engberts, J. B. F. N.; Wynberg, H. *Synth. Commun.* **1972**, *2*, 415. (c) Boar, R. B.; Hawkins, D. W.; McGhie, J. F.; Barton, D. H. R. *J. Chem. Soc., Perkin Trans. 1* **1973**, 654. (d) Schultz, A. G.; Fu, W. Y.; Lucci, R. D.; Kurr, B. G.; Lo, K. M.; Boxer, M. *J. Am. Chem. Soc.* **1978**, *100*, 2140. (e) Myrboh, B.; Singh, L. W.; Ila, H.; Junjappa, H. *Synth.* **1982**, 307. (f) Euerby, M. R.; Waigh, R. D. *Synth. Commun.* **1986**, *16*, 779. (g) Zaman, S. S.; Sarmah, P.; Barua, N. C.; Sharma, R. P. *Chem. Ind.* **1989**, 806. (h) Guziec, F. S., Jr.; Wasmund, L. M. *Tetrahedron Lett.* **1990**, *31*, 23.

(7) Back, T. G.; Yang, K.; Krouse, H. R. *J. Org. Chem.* **1992**, *57*, 1986.

(8) Back, T. G.; Birss, V. I.; Edwards, M.; Krishna, M. V. *J. Org. Chem.* **1988**, *53*, 3815.

(9) For other examples of deselenizations with nickel boride, see: (a) Barton, D. H. R.; Britten-Kelly, M. R.; Ferreira, D. *J. Chem. Soc., Perkin Trans. 1* **1978**, 1682. (b) Barton, D. H. R.; Lusinchi, X.; Milliet, P. *Tetrahedron Lett.* **1982**, *23*, 4949. (c) Ninomiya, I.; Hashimoto, C.; Kiguchi, T.; Barton, D. H. R.; Lusinchi, X.; Milliet, P. *Tetrahedron Lett.* **1985**, *26*, 4187.

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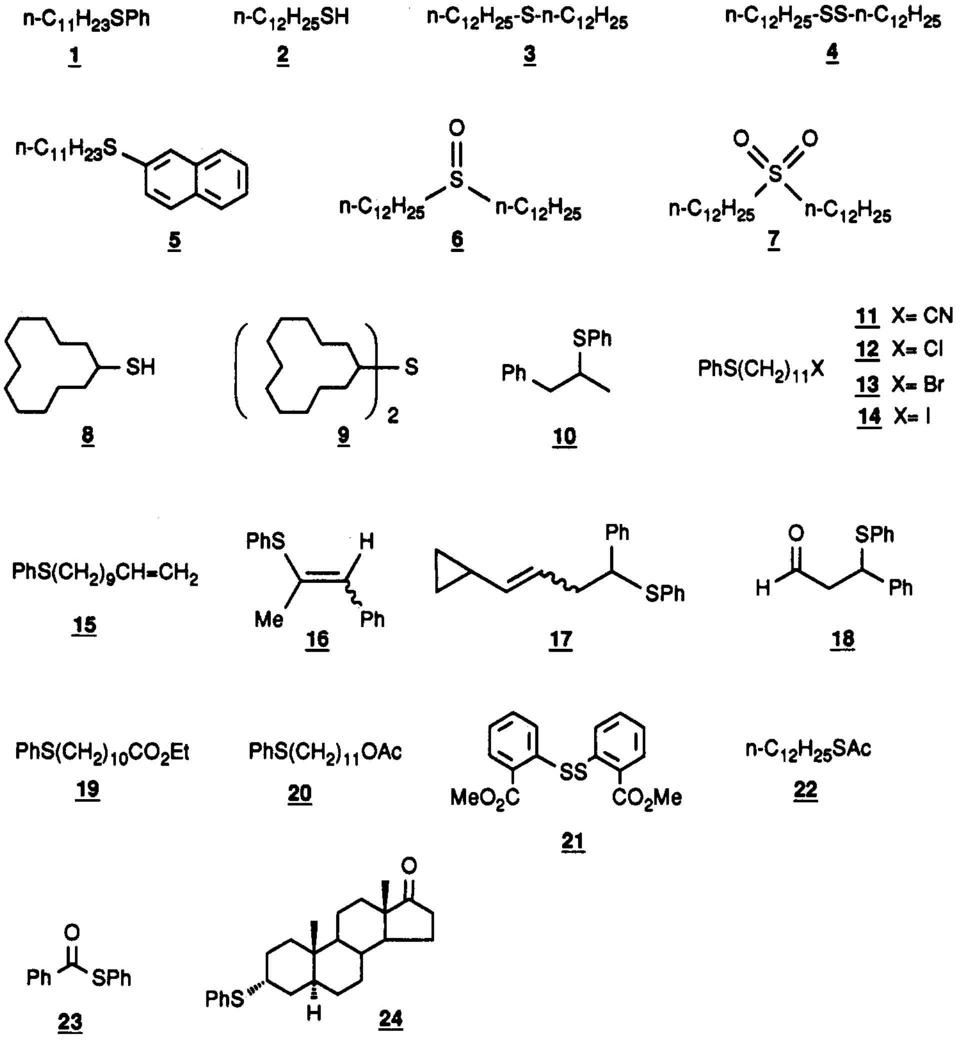
Chart I



on previous considerations,[7] as was the use of a 3:1 molar ratio of sodium borohydride to $NiCl_2{\cdot}6H_2O$.[8] Typically, reactions were performed at 0 °C for 15 min in an open vessel without protection from the atmosphere, by addition of the sodium borohydride in small portions to a solution of the organosulfur compound and $NiCl_2{\cdot}6H_2O$ in the above solvent.[10] The substrates are shown in Chart I, and the results are summarized in Table I. Several examples with cobalt boride generated in a similar manner from cobalt chloride hexahydrate ($CoCl_2{\cdot}6H_2O$) are also included for comparison.

Since the phenylthio group is commonly encountered in synthetic transformations based on organosulfur chemistry, we first examined the desulfurization of 1-(phenylthio)undecane (1) as a typical substrate and measured the yield of *n*-undecane by GC. Although aryl–sulfur bonds are also cleaved under these conditions,[11] the benzene so formed was not measured due to masking by the solvent. Entries 1–4 in Table I show that a high yield of *n*-undecane was produced when 3.5 mol of nickel boride (i.e., from 7.0 mol of $NiCl_2{\cdot}6H_2O$) were employed per mol of substrate. Smaller amounts of the reductant gave incomplete reactions, and 5.0 mol produced little further improvement. In general, therefore, the reactions in Table I with other substrates were also performed with 3.5 mol of nickel boride to facilitate comparisons, although in some specific cases larger or smaller amounts were also used as required. Desulfurizations of 1 with cobalt boride under comparable conditions are given in entries 5–7.

The yields of the products formed in Table I were either measured by GC and the identities of the products were confirmed by GC–mass spectrometry or the products were isolated and compared to authentic samples. In addition to the products indicated in Table I, unreacted starting materials were also detected in most of the examples and account for most of the remaining mass balance.[12] Table I indicates that a large variety of organosulfur compounds are smoothly desulfurized with nickel boride under these conditions. Both primary and secondary thiols (2 and 8 in entries 8 and 20, respectively) afforded the corresponding hydrocarbons in good yield. Sulfides and disulfides proved more difficult to reduce than thiols, particularly in the case of the more sterically hindered secondary sulfide 9 in entries 21 and 22, which afforded only traces of cyclododecane in contrast to the corresponding thiol 8 in entry 20. Presumably because of their greater reactivity,

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[10] It is essential to generate the nickel or cobalt boride in the presence of the organosulfur compound as the reagents undergo a rapid loss of desulfurization activity. Once lost, the activity of aged nickel boride is only partly restored by the further addition of sodium borohydride or by treatment with hydrogen under pressure (see ref 7).

[11] This is evident from the examples in entries 14 and 15 in Table I, where naphthalene was produced in high yield from cleavage of the arylthio bond and from the successful previous desulfurization of benzo- and dibenzothiophenes (ref 7).

[12] Typical mass balances accounted for 85–95% of the organic material present. Small amounts (ca. 5%) of the unconsumed starting materials remained trapped inside the nickel boride precipitate and could be released by dissolution of the latter in strong acids.

Table I. Desulfurization with Nickel and Cobalt Borides

entry	substrate	metal boride[a] (mol)	products[b] (yield %)
1	**1**	Ni_2B (1.0)	n-$C_{11}H_{24}$ (45)
2		Ni_2B (2.5)	(62)
3		Ni_2B (3.5)	(86)
4		Ni_2B (5.0)	(90)
5		Co_2B (1.5)	(42)
6		Co_2B (3.5)	(76)
7		Co_2B (3.5)[c]	(84)
8	**2**	Ni_2B (3.5)	n-$C_{12}H_{26}$ (86)
9	**3**	Ni_2B (3.5)	n-$C_{12}H_{26}$ (57)
10		Co_2B (3.5)	(7)
11	**4**	Ni_2B (3.5)	n-$C_{12}H_{26}$ (48)
12		Co_2B (3.5)[d]	(21)
13		Co_2B (7.0)	(50)
14	**5**	Ni_2B (3.5)	naphthalene (87) + n-$C_{11}H_{24}$ (67)
15		Co_2B (3.5)	(56) (63)
16	**6**	Ni_2B (3.5)	n-$C_{12}H_{26}$ (37) + (n-$C_{12}H_{25})_2S$ (54)
17		Ni_2B (7.0)	(67) (23)
18	**7**	Ni_2B (3.5)	n-$C_{12}H_{26}$ (trace)
19		Ni_2B (7.0)	(14)
20	**8**	Ni_2B (3.5)	cyclododecane (80)
21	**9**	Ni_2B (3.5)	cyclododecane (3)
22		Ni_2B (7.0)	(4)
23	**10**	Ni_2B (3.5)	$PhCH_2CH_2CH_3$ (78)
24	**11**	Ni_2B (3.5)	n-$C_{12}H_{25}NH_2$ (86)[e]
25	**12**	Ni_2B (3.5)	n-$C_{11}H_{23}Cl$ (82)
26		Co_2B (3.5)	n-$C_{11}H_{23}Cl$ (65)
27	**13**	Ni_2B (3.5)	n-$C_{11}H_{23}Br$ (11) + n-$C_{11}H_{24}$ (76)
28		Ni_2B (7.0)	n-$C_{11}H_{24}$ (81)
29		Co_2B (3.5)	(52)
30	**14**	Ni_2B (3.5)	n-$C_{11}H_{24}$ (85)
31	**15**	Ni_2B (1.0)	n-$C_{11}H_{24}$ (22)
32		Ni_2B (3.5)	(83)
33		Co_2B (3.5)	n-$C_{11}H_{24}$ (41) + n-$C_9H_{19}CH{=}CH_2$ (5)
34	**16**	Ni_2B (3.5)	$PhCH_2CH_2CH_3$ (75)
35	**17**	Ni_2B (3.5)	n-$C_7H_{15}Ph$ (24)[e] + 1-cyclopropyl-4-phenylbutane (52)[e]
36	**18**	Ni_2B (3.5)	$PhCH_2CH_2CHO$ (14)[e] + $PhCH_2CH_2CH_2OH$ (75)[e]
37	**19**	Ni_2B (3.5)	n-$C_{10}H_{21}CO_2Et$ (72)
38	**20**	Ni_2B (3.5)	n-$C_{11}H_{23}OAc$ (83)
39	**21**	Ni_2B (3.5)	$PhCO_2Me$ (64)
40	**22**	Ni_2B (3.5)	n-$C_{12}H_{24}$ (75)
41	**23**	Ni_2B (3.5)	$PhCH_2OH$ (91)[e]
42	**24**	Ni_2B (3.5)	androstan-17-one (25)[d,e] + androstan-17β-ol (46)[d,e]

[a] The number of moles of boride per mole of substrate is shown; 2 mol of Ni(II) or Co(II) salt and 6 mol of $NaBH_4$ were used to generate each mole of boride. The solvent was MeOH–THF (3:1) unless otherwise indicated. [b] GC yields are reported unless otherwise indicated. [c] The solvent was MeOH–THF–H_2O (27:10:3). [d] The solvent was MeOH–THF (1:1). [e] Isolated yield.

thiol byproducts were not observed in the reductions of sulfides or disulfides. Sulfoxide **6** afforded a substantial amount of the corresponding sulfide **3** in addition to n-dodecane when desulfurized with the standard 3.5 mol of nickel boride (entry 16), and a larger excess of the boride reagent was required to obtain a good yield of the hydrocarbon (entry 17). This experiment also indicates that sulfides are intermediates in the reduction of sulfoxides by this method. The corresponding sulfone **7** was largely unchanged, even with 7 mol of nickel boride (entries 18 and 19).

Our previous work on benzo- and dibenzothiophene derivatives revealed that hydroxyl, carboxyl, and amino groups are stable to nickel boride and do not interfere with desulfurization.[7] Table I now shows the relative ease of desulfurization with nickel boride compared to the competing reduction of other functionalities. Thus, aryl (entries 14, 15, 23, 34, 35, 36, 39, and 41), chloro (entry 25), and ester groups (entries 37–39) remained intact, while iodo (entry 30), nitrile (entry 24), and olefinic (entries 31, 32, 34, and 35) functions were completely reduced during desulfurization. The reductions of cyclopropane (entry 35), bromo (entry 27), aldehyde (entry 36), and ketone (entry 42) moieties competed with desulfurization to various extents. It is interesting to note that cleavage of the cyclopropane ring in **17** (entry 35) occurred at the tertiary carbon atom to afford 1-phenylheptane, rather than the isoheptyl isomer. This contrasts with other catalytic hydrogenolyses of alkyl- and arylcyclopropanes, where the cyclopropane ring usually cleaves preferentially between the least-substituted carbons.[13] Entries 40 and 41 indicate that thioesters undergo both alkyl–S cleavage and acyl–S scission with accompanying reduction of the carbonyl group.

All of the examples in Table I where cobalt boride was employed instead of nickel boride under comparable conditions (entries 1–4 vs 5–7, 9 vs 10, 11 vs 12, 14 vs 15, 25 vs 26, 27 vs 29, and 32 vs 33) indicate that cobalt boride is the less powerful reductant, affording lower yields of desulfurized products. Attempts were also made to generate other metal borides[2] in a similar fashion from the reactions of various salts of Mo, Ti, Cu, and Fe with sodium borohydride, but these proved either wholly ineffective or considerably inferior to either the Ni or Co reagents in desulfurization processes. Moreover, the use of lithium borohydride in place of sodium borohydride for the generation of nickel boride from $NiCl_2{\cdot}6H_2O$ gave comparable results, while sodium cyanoborohydride failed

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(13) Newham, J. *Chem. Rev.* **1963**, *63*, 123.

Table II. Desulfurization of 1-(Phenylthio)undecane (1) with Deuterated Reagents and Solvents

entry	reagents and solvents	ratio of n-$C_{11}H_{24}$:n-$C_{11}H_{23}D$
1	$NiCl_2/NaBH_4/CH_3OD/THF$	60:40
2	$NiCl_2 \cdot 6H_2O/NaBD_4/CH_3OH/THF$	43:57
3	$NiCl_2 \cdot 6H_2O/NaBH_4/CD_3OH/THF$	100:0
4	$NiCl_2 \cdot 6H_2O/NaBH_4/CH_3OH/THF$-$d_8$	100:0
5	$NiCl_2/NaBD_4/CH_3OD/THF$	3:97

to produce a boride reagent capable of desulfurization under the usual conditions.

The fate of the sulfur that is removed from the substrate during treatment with nickel boride is of relevance in attempts to develop an alternative procedure that would permit the use of catalytic amounts of metal borides in concert with an external source of hydrogen gas. We found that no hydrogen sulfide was liberated during nickel boride-mediated desulfurization, as lead sulfide formation was not observed when the gas evolved during the reaction was tested with lead acetate. This suggests that the sulfur remains in the spent nickel boride precipitate, probably in the form of nickel or boron sulfides. Elemental analyses of the dried precipitate indicated the presence of sulfur, although the heterogeneous nature of the substance made it difficult to get consistent values. Finally, the precipitate was digested in phosphoric acid while a stream of nitrogen was passed through the solution and exhausted through a series of traps containing lead acetate solution. The formation of lead sulfide (PbS) confirmed the liberation of hydrogen sulfide according to eq 4, accounting for 84%

$$Ni_2B{\cdot}S \xrightarrow{H^+} H_2S \xrightarrow{Pb^{+2}} PbS \qquad (4)$$

of the total sulfur after isolation and weighing of the PbS precipitate. The retention of sulfur by the spent nickel boride therefore presents a substantial obstacle to the use of the boride in a catalytic role, which would be desirable for industrial applications.

Labeling Studies. Since information concerning the source of the hydrogen that is incorporated into the product could provide insight into the mechanism of the desulfurization, we performed a series of deuterium labeling experiments in the desulfurization of 1 with nickel boride. The amount of deuterioundecane present in the product undecane was measured by mass spectrometry, and the results are summarized in Table II. Entries 1 and 2 reveal that the hydrogen derives in roughly equal proportions from the sodium borohydride and the protic solvent. This rules out any mechanism where the sulfur compound is first activated by prior complexation to either the initial Ni(II) species or to the nickel boride generated in situ, followed by hydride attack from the sodium borohydride upon the α-carbon with displacement of the sulfur moiety. The preceding scenario would require the sodium borohydride to function as the sole source of the label. Similar activation and nucleophilic attack by hydride has been suggested in the reduction of nitriles to amines with cobalt boride.[14] On the other hand, the results in entries 1 and 2 are consistent with the formation of dihydrogen (or H-D in the above labeling experiments) via eqs 1 and 2 and implicate it in the desulfurization process.[15] Its adsorption and activation upon the nickel boride surface may be followed by the formation of a transient nickel hydride intermediate, according to previous arguments.[7]

Entries 3 and 4 in Table II were designed to test the possibility of a radical mechanism, such as has been proposed in desulfurizations with Raney nickel.[16] Both CD_3OH and THF-d_8 are good hydrogen donors that would be expected to introduce deuterium into the hydrocarbon product via eq 5 if alkyl radicals were intermediates in the

$$R^{\bullet} + CD_3OH \text{ (or THF-}d_8) \rightarrow RD + {}^{\bullet}CD_2OH \text{ (or }{}^{\bullet}\text{THF-}d_7) \qquad (5)$$

process. Similar hydrogen abstraction from THF was observed in the reduction of organohalides with cobalt aluminide.[14b] However, the absence of measurable amounts of deuterium in the desulfurized product argues against a radical mechanism in the present case.

Finally, entry 5 demonstrates that the use of both sodium borodeuteride and CH_3OD provides a convenient method for the preparation of deuterium-labeled hydrocarbons from organosulfur compounds.

Stereochemistry. Knowledge of the stereochemistry of nickel boride-mediated desulfurization could also provide insight into the mechanism of the process. We therefore investigated the reduction of a substrate in which the sulfur atom is attached to a chiral carbon atom of known configuration, using nickel boride prepared with sodium borodeuteride and CH_3OD (i.e., the conditions of entry 5 in Table II). For this purpose, we started with 3α- and 3β-chlorocholestane[17] (**25** and **28**, respectively) and converted them into the corresponding known 3β- and 3α-phenylthio derivatives[18] **26** and **29**, respectively, by reaction with sodium benzenethiolate in DMF, with inversion of configuration at C-3 (Scheme I). When the 3β-isomer **26** was desulfurized with labeled reagents, the corresponding 3-deuteriocholestane revealed a single signal at δ 1.66 in its ^2H-NMR spectrum. Similar treatment of the 3α-isomer **29** afforded a product with a ^2H-NMR signal at δ 1.19 containing only a small amount (<10%) of the epimer with the resonance at δ 1.66. Since equatorial protons (or deuterons) at C-3 of steroids are known to resonate further downfield than axial ones,[19] we assign the 3β-deuterio structure **27** to the product derived from **26** and the 3α-deuterio structure **30** to that obtained from **29**. Our assignments are in accord with those made previously for 3α- and 3β-deuterioandrostanes on the basis of their deuterium chemical shifts[20] but contrary to those made for **27** and **30** based on the corresponding deuterium

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(14) (a) Heinzman, S. W.; Ganem, B. *J. Am. Chem. Soc.* **1982**, *104*, 6801. (b) Osby, J. O.; Heinzman, S. W.; Ganem, B. *J. Am. Chem. Soc.* **1986**, *108*, 67.

(15) The reason for the deviation from a 50:50 ratio of labeled vs unlabeled undecane (i.e., corresponding to the intermediacy of pure H-D) is unclear as neither the relative contributions to hydrogen generation from eqs 1 and 2 nor their precise mechanisms are known.

(16) (a) Badger, G. M.; Sasse, W. H. F. *J. Chem. Soc.* **1957**, 3862. (b) Hauptmann, H.; Walter, W. F.; Marino, C. *J. Am. Chem. Soc.* **1958**, *80*, 5832.

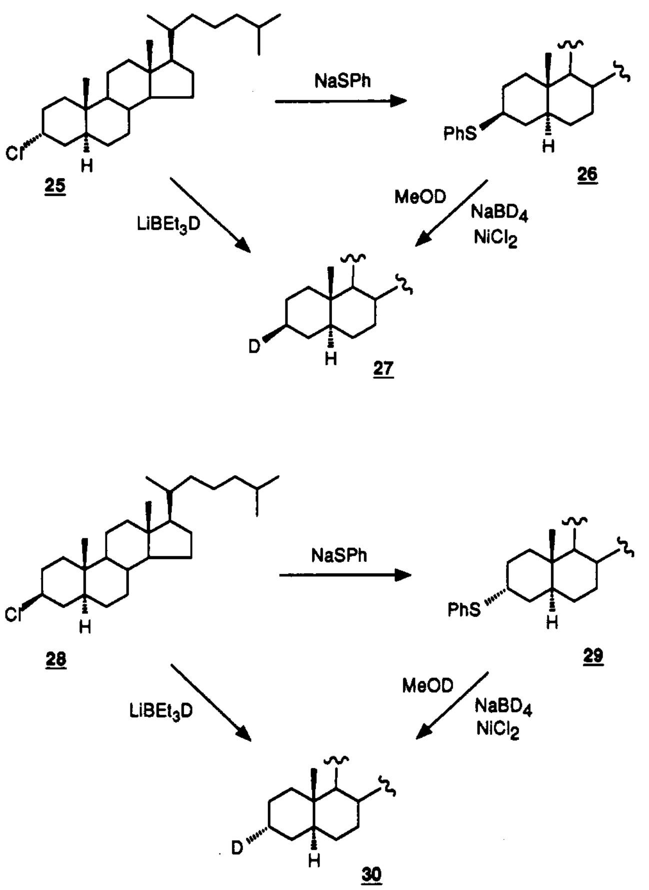
(17) (a) Shoppee, C. W. *J. Chem. Soc.* **1946**, 1138. (b) Gschwendtner, W.; Schneider, H.-J. *J. Org. Chem.* **1980**, *45*, 3507.

(18) (a) King, J. F.; Abikar, K.; Deaken, D. M.; Pews, R. G. *Can. J. Chem.* **1968**, *46*, 1. (b) Jones, D. N.; Green, M. J. *J. Chem. Soc. C* **1967**, 532.

(19) This is generally observed in cyclohexanes; see: Jackman, L. M.; Sternhell, S. *Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry*, 2nd ed.; Pergamon Press: Oxford, 1969; p 238.

(20) Hanson, J. R.; Wadsworth, H. J.; Hull, W. E. *J. Chem. Soc., Perkin Trans. 1* **1980**, 1381.

Scheme I

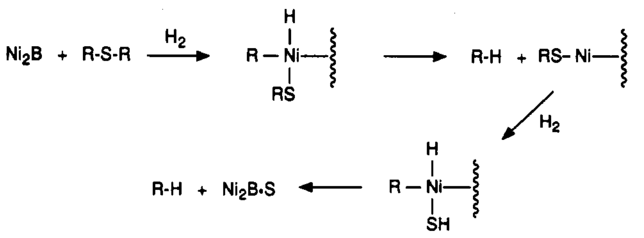


signal widths.[21] In view of the discrepancy in the literature, we wished to further verify our assignments, and so we also reduced the 3α- and 3β-chlorocholestanes **25** and **28**, respectively, with lithium triethylborodeuteride, a reagent that is known to reduce alkyl halides with inversion of configuration.[22] The formation of **27** from **25** and **30** from **28** in these experiments confirms the assignment of the 3β-deuterio (equatorial) configuration to **27** and the 3α-deuterio (axial) configuration to **30**. These results are summarized in Scheme I and indicate that, surprisingly, *desulfurization with nickel boride occurs in a highly stereospecific fashion with retention of configuration.*

Conclusions

The above results indicate that a wide variety of organosulfur compounds can be rapidly desulfurized with nickel boride under remarkably mild conditions. Since nickel boride is inexpensive, convenient to prepare and easily removed after completion of the reaction, and can be used in an open vessel without protection from the atmosphere, it is a particularly useful reagent for this purpose. Cobalt and other metal borides are not as effective as nickel boride under these conditions.

Scheme II



Deuterium-labeling studies rule out a mechanism involving activation of the substrate by complexation of its sulfur atom with nickel boride, followed by hydride attack from sodium borohydride upon the α-carbon. Similarly, labeling experiments with hydrogen-donor solvents, as well as the observed stereospecificity, are inconsistent with a radical mechanism. On the other hand, the labeling experiments show that the deuterium incorporated into the product originates from both the sodium borohydride and the solvent, suggesting that dihydrogen is involved in the process. These results are consistent with the formation of dihydrogen via eqs 1 and 2, followed by its adsorption on to the nickel boride surface, and then, as according to previous arguments,[7] its conversion into a nickel hydride species. Oxidative addition–reductive elimination mechanisms of nickel and other transition metals are well-precedented and occur by a variety of mechanisms with different stereochemical outcomes.[23] We tentatively propose that a stereospecific oxidative addition of the C–S bond of the substrate to the nickel atom occurs, followed by a stereospecific reductive elimination of C–H, as shown in Scheme II. For example, a three-center mechanism for the oxidative addition step[24] could be accompanied by retention, and it has been reported that reductive eliminations from other metal centers involving C–H bond formation also occur with retention of configuration at a chiral carbon center.[25] While our results are consistent with such a mechanism, they do not unequivocally rule out an alternative possibility where both steps occur with inversion, again resulting in the overall observed retention of stereochemistry. The role played by the boron in nickel boride remains unclear, although a previous study[26] has indicated that it can reside in several different environments that affect the reactivity of the reagent and that it increases the electron density on the nickel. This would be expected to facilitate the oxidative addition step by stabilizing the increasing positive character of the nickel. However, firm conclusions regarding this point are difficult to make because of the lack of information about the precise structures of nickel and other metal borides.

Experimental Section

Gas chromatographic analyses were performed on an instrument equipped with a flame ionization detector and a 15-m DB-17 Megabore column (J and W Scientific Co.). Yields were measured by integration relative to an internal standard (*n*-

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(21) Tureček, F.; Vereš, K.; Kočovsky, P.; Pouzar, V.; Fajkoš, J. *J. Org. Chem.* **1983**, *48*, 2233. These authors assigned the 3α-deuterio and 3β-deuterio configurations **30** and **27** to the epimers with ^{2}H resonances at δ 1.64 ($W_{1/2}$ = 6.9 Hz) and δ 1.20 ($W_{1/2}$ = 4.6 Hz), respectively, on the basis of the expected broader ^{2}H signal width for the axial isomer **30**. However, the differences in the peak widths are relatively modest and, in our hands, proved difficult to reproduce exactly, presumably because of instabilities in the magnetic field. We therefore favor the assignments made by Hanson (ref 20) based on ^{2}H chemical shifts rather than signal widths.

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decane, *n*-undecane, or *n*-dodecane), and corrections were made for relative response factors. GC yields are based on averages of at least three runs, and the identities of the products were confirmed by comparison of their GC–mass spectra with those of authentic samples. In those cases where the products were isolated, their identities were confirmed by comparison of their IR, NMR, and mass spectra with those of authentic samples or literature values. Isolations were performed by preparative TLC on Analtech 20 × 20-cm glass plates coated with 1 mm of silica gel GF or by flash chromatography on Merck silica gel (60–200 mesh). ^{2}H-NMR spectra were obtained on a Bruker AM 400 spectrometer in the FT mode with a pulse width of 10 μs, unlocked and proton-coupled, using chloroform as the solvent and deuteriochloroform as the internal standard. We thank Drs. T. S. Sorensen and R. Yamdagni for assistance with the latter experiments.

Preparation of Starting Materials. Of the compounds in Chart I, **2** and **3** were purchased from commercial sources while the known compounds **1**,[27] **4**,[28] **5**,[27] **6**,[29] **7**,[30] **8**,[31] **9**,[32] **10**,[33] **16**,[34] **18**,[35] **19**,[36] **21**,[37] **22**,[38] and **23**[39] were prepared by routine methods[40] and had properties in close agreement with those reported previously. Other starting materials are described below. All starting materials were purified by standard methods until they were homogeneous on TLC and/or had GC purities of >98%.

12-(Phenylthio)dodecanenitrile (11). 11-Bromoundecanol (2.97 g, 11.8 mmol), sodium cyanide (Caution: toxic) (2.93 g, 59.7 mmol), and sodium iodide (3.47 g, 23.2 mmol) were refluxed overnight in 10 mL of water and 20 mL of methanol. The mixture was diluted with ether, washed several times with water, and dried ($MgSO_4$). After evaporation of the solvent, the crude nitrile was refluxed with 2 mol equiv of thionyl chloride in carbon tetrachloride overnight, and the mixture was washed cautiously with water, NaOH solution, and brine and dried ($MgSO_4$). The solvent was removed, and the crude chloride was treated with equimolar amounts of benzenethiol and sodium methoxide in methanol for 30 min. The mixture was concentrated under vacuum, taken up in ether, washed with water and brine, and dried ($MgSO_4$) to afford 2.58 g (99%) of **11** as a homogeneous colorless oil: IR (film) 2246 cm^{-1}; ^{1}H-NMR δ 7.35–7.10 (m, 5 H), 2.92 (t, J = 7.2 Hz, 2 H), 2.33 (t, J = 7.0 Hz, 2 H), 1.70–1.55 (m, 4 H), 1.50–1.20 (m, 14 H); mass spectrum (m/z, relative intensity) 289 (M$^+$, 89), 249 (5), 180 (16), 110 (100); exact mass calcd for $C_{18}H_{27}NS$ 289.1864, found 289.1872.

1-Chloro-11-(phenylthio)undecane (12). 11-Bromoundecanol (5.46 g, 21.7 mmol) was treated with benzenethiol and sodium methoxide in methanol at reflux for 3 h and worked up as in the preceding procedure, followed by crystallization from hexane to afford 5.52 g (91%) of 11-(phenylthio)-1-undecanol, mp 67–68 °C. Chlorination of the latter as in the preceding procedure afforded 83% of **12** as a homogeneous colorless oil: ^{1}H-NMR δ 7.35–7.10 (m, 5 H), 3.53 (t, J = 6.7 Hz, 2 H), 2.91 (t, J = 7.3 Hz, 2 H), 1.85–1.50 (m, 4 H), 1.50–1.20 (m, 14 H); mass spectrum (m/z, relative intensity) 298 (M$^+$, 22), 110 (100); exact mass calcd for $C_{17}H_{27}ClS$ 298.1522, found 298.1513.

1-Bromo-11-(phenylthio)undecane (13). 11-(Phenylthio)-1-undecanol (953 mg, 3.40 mmol; prepared as described above) and triphenylphosphine (1.08 g, 4.13 mmol) were dissolved in 20 mL of THF. Carbon tetrabromide (1.37 g, 4.14 mmol) was added in portions, and the mixture was refluxed for 3 h. The mixture was diluted with pentane, filtered, and separated by flash chromatography (elution with 10% ethyl acetate–hexane) to give 1.10 g (94%) of **13** as a yellow oil: ^{1}H-NMR δ 7.35–7.20 (m, 5 H), 3.40 (t, J = 6.9 Hz, 2 H), 2.91 (t, J = 7.3 Hz, 2 H), 1.85 (m, 2 H), 1.65 (m, 2 H), 1.50–1.20 (m, 14 H); mass spectrum (m/z, relative intensity) 342 (M$^+$, 33), 123 (22), 110 (100); exact mass calcd for $C_{17}H_{27}BrS$ 342.1016, found 342.1006.

1-Iodo-11-(phenylthio)undecane (14). 11-(Phenylthio)-1-undecanol, prepared as described above, was converted into its tosylate with *p*-toluenesulfonyl chloride and pyridine. The crude tosylate (1.55 g, 3.57 mmol) was refluxed overnight with excess sodium iodide in acetone. The mixture was concentrated, diluted with water, and extracted 3× with ether. The ether extracts were combined, washed with brine, and dried ($MgSO_4$). Removal of the solvent in vacuo afforded 940 mg (67%) of **14** as a homogeneous yellow oil: ^{1}H-NMR δ 7.35–7.20 (m, 5 H), 3.19 (t, J = 7.0 Hz, 2 H), 2.92 (t, J = 7.3 Hz, 2 H), 1.82 (m, 2 H), 1.65 (m, 2 H), 1.50–1.20 (m, 14 H); mass spectrum (m/z, relative intensity) 390 (M$^+$, 40), 262 (20), 110 (100); exact mass calcd for $C_{17}H_{27}IS$ 390.0837, found 390.0893.

11-(Phenylthio)-1-undecene (15). The tosylate of 10-undecen-1-ol was treated with benzenethiol and sodium methoxide as in the preparation of **11** to afford **15** as a homogeneous colorless oil: IR (film) 1638 cm^{-1}; ^{1}H-NMR δ 7.35–7.10 (m, 5 H), 5.81 (m, 1 H), 5.05–4.90 (m, 2 H), 2.92 (t, J = 7.3 Hz, 2 H), 2.03 (m, 2 H), 1.72–1.20 (m, 14 H); mass spectrum (m/z, relative intensity) 262 (M$^+$, 11), 123 (30), 110 (100); exact mass calcd for $C_{17}H_{26}S$ 262.1755, found 262.1755.

1-Cyclopropyl-4-phenyl-4-(phenylthio)-1-butene (17). *n*-Butyllithium in hexane (4.23 mmol) was added dropwise to a solution of (cyclopropylmethyl)triphenylphosphonium bromide (1.68 g, 4.23 mmol) in 25 mL of dry THF. The mixture was stirred for 3 h at room temperature, and then 3-(phenylthio)hydrocinnamaldehyde (**18**)[35] (1.02 g, 4.20 mmol) in THF was added. The mixture was refluxed overnight, and then it was diluted with water and extracted with 3 × 20 mL of ether. The combined extracts were washed with brine, dried ($MgSO_4$), and concentrated. The residue was separated by flash chromatography (elution with 10% ethyl acetate in hexane) to afford 340 mg (29%) of **17** as a colorless oil: IR (film) 1653, 1638 cm^{-1}; ^{1}H-NMR δ 7.31–7.16 (m, 10 H), 5.50–5.15 (m, 1 H), 5.03–4.70 (m, 1 H), 4.21 (m, 1 H), 2.95–2.55 (m, 2 H), 1.50–1.20 (m, 1 H), 0.64 (m, 2 H), 0.27 (m, 2 H); mass spectrum (m/z, relative intensity) 280 (M$^+$, 3), 199 (100); exact mass calcd for $C_{19}H_{20}S$ 280.1286, found 280.1282.

11-(Phenylthio)undecyl Acetate (20). 11-(Phenylthio)-1-undecanol (502 mg, 1.79 mmol), prepared as in the procedure for **12**, was acetylated with acetic anhydride in pyridine at room temperature overnight to afford 538 mg (93%) of **20**: mp 44–44.5 °C; IR (Nujol) 1734, 1249, 1039 cm^{-1}; ^{1}H-NMR δ 7.35–7.10 (m, 5 H), 4.05 (t, J = 6.7 Hz, 2 H), 2.92 (t, J = 7.3 Hz, 2 H), 2.05 (s, 3 H), 1.65–1.50 (m, 4 H), 1.50–1.20 (m, 14 H); mass spectrum (m/z, relative intensity) 322 (M$^+$, 78), 110 (100). Anal. Calcd for $C_{19}H_{30}O_2S$: C, 70.76; H, 9.38. Found: C, 70.35; H, 9.33.

3α-(Phenylthio)androstan-17-one (24). 3β-Hydroxyandrostan-17-one (944 mg, 3.25 mmol) was converted into its tosylate and then treated with sodium benzenethiolate, prepared from benzenethiol (4.00 mmol) and sodium methoxide (4.00 mmol), in 10 mL of methanol and 10 mL of DMF at reflux for 3.5 h. The mixture was then poured into ice–water, and the precipitate was filtered, dried, and purified by flash chromatography (elution with 5% ethyl acetate-hexane), followed by recrystallization from chloroform–hexane, to afford 755 mg (61%) of **24**: mp 190–191 °C; IR (Nujol) 1738, 1584, 1015, 743 cm^{-1}; ^{1}H-NMR δ 7.40–7.18 (m, 5 H), 3.67 (m, 1 H), 2.45 (m, 1 H), 2.09 (m, 1 H), 0.87 (s, 3 H), 0.84 (s, 3 H); mass spectrum (m/z, relative intensity) 382 (M$^+$, 100), 273 (23), 255 (42), 110 (59). Anal. Calcd for $C_{25}H_{34}OS$: C, 78.48; H, 8.96. Found: C, 78.53; H, 8.97.

3β-(Phenylthio)cholestane (26). Triphenylphosphine (0.744 g, 2.84 mmol) and 3β-cholestanol (1.10 g, 2.84 mmol) were refluxed for 24 h in 20 mL of carbon tetrachloride. The mixture was then filtered, concentrated, and separated by flash chromatography (elution with 10% ethyl acetate–hexane) to afford 563 mg (51%)

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of 3α-chlorocholestane (**25**) [mp 103–104 °C (lit.[17a] mp 105 °C); ^{1}H-NMR δ 4.51 (m, 3β-H) (lit.[17b] δ 4.48)], along with 443 mg (40%) of unreacted starting material. Compound **25** (272 mg, 0.670 mmol) was treated with 1.1 molar equiv of sodium benzenethiolate (prepared from benzenethiol and sodium methoxide) in 10 mL of dry DMF at reflux for 1 h. The mixture was diluted with ether, washed with 10% HCl, 5% NaOH, and brine, and dried ($MgSO_4$). Evaporation of the solvent afforded 280 mg (88%) of **26**: mp 77–79 °C (lit.[18a] mp 79–80 °C); ^{1}H-NMR δ 3.06 (m, 3α-H) (lit.[18b] δ 2.92).

3α-(Phenylthio)cholestane (29). 3β-Chlorocholest-4-ene (1.07 g, 2.63 mmol) was hydrogenated in 30 mL of ether in the presence of 100 mg of 10% Pd/C under positive pressure (hydrogen balloon). The catalyst was removed by filtration, and the solvent was evaporated to afford 1.03 g (98%) of 3β-chlorocholestane (**28**): mp 110–112 °C (lit.[17a] mp 115 °C); ^{1}H-NMR δ 3.86 (m, 3α-H) (lit.[17b] δ 3.86). Compound **28** (179 mg, 0.440 mmol) was treated with sodium benzenethiolate as in the preceding procedure to afford 199 mg (94%) of **29**: mp 105–106 °C (lit.[18a] mp 105–106 °C); ^{1}H-NMR δ 3.66 (m, 3β-H) (lit.[18b] δ 3.57).

Desulfurization with Nickel Boride (See Table I). General Procedure for the Use of 3.5 Molar Equiv of Ni_2B. The organosulfur compound (ca. 0.5 mmol) and $NiCl_2 \cdot 6H_2O$ (3.5 mmol) were dissolved in 15 mL of methanol–THF (3:1) in a magnetically stirred Erlenmeyer flask at 0 °C. Sodium borohydride (10.5 mmol) was added in small portions (Caution: vigorous reaction with hydrogen evolution). The immediate formation of a black precipitate was observed, and the mixture was stirred for an additional 15 min. The precipitate was then filtered through Celite and washed with methanol–THF, and 100 μL of the internal standard was added to the filtrate. The yield of the desulfurized product was measured by GC, and the identity of the product was confirmed by comparing its mass spectrum with that of an authentic sample. Variations to this procedure are indicated in Table I. Desulfurizations performed with cobalt boride were performed in the same way, using $CoCl_2 \cdot 6H_2O$ instead of $NiCl_2 \cdot 6H_2O$. Caution: Appropriate care should be exercised in the handling and disposal of nickel and cobalt salts; nickel salts in particular are suspected carcinogens.

Those products in Table I that were isolated were generally well-known compounds easily identified by comparison with authentic samples. Entry 35 was an exception which is therefore described in full. Compound **17** (197 mg, 0.700 mmol) was desulfurized with $NiCl_2 \cdot 6H_2O$ (1.17 g, 4.93 mmol) and sodium borohydride (560 mg, 14.8 mmol) as in the general method. The reaction mixture was filtered through Celite, concentrated, and partitioned between water and dichloromethane. The water layer was extracted twice with dichloromethane, the combined organic layers were dried ($MgSO_4$) and concentrated, and the resulting residue was separated by preparative TLC in hexane to afford 29 mg (24%) of *n*-heptylbenzene, R_f 0.78, with ^{1}H-NMR and IR spectra as reported in the literature,[41] and mass spectrum (*m/z*, relative intensity) 176 (M^+, 26), 91 (100). A second band gave 63 mg (52%) of 1-cyclopropyl-4-phenylbutane: R_f 0.67, IR (film) 1602, 1496, 744, 698 cm^{-1}; ^{1}H-NMR δ 7.35–7.10 (m, 5 H), 2.61 (t, J = 7.6 Hz, 2 H), 1.70–1.15 (m, 6 H), 0.63 (m, 1 H), 0.41 (m, 2 H), 0.00 (m, 2 H); mass spectrum (*m/z*, relative intensity) 174 (M^+, 13), 91 (100); exact mass calcd for $C_{13}H_{18}$ 174.1409, found 174.1400. A more polar band, R_f 0.22, provided 41 mg (21%) of unreacted starting material.

Deuterium-Labeling Studies. Of 1-(Phenylthio)undecane (1). Compound **1** was subjected to the general desulfurization procedure described above, except that various combinations (see Table II) of sodium borodeuteride (98 atom % D), CH_3OD (99.5 atom % D), CD_3OH (99 atom % D), and THF-d_8 (99 atom % D) were used in place of the usual reagents and solvents. In those experiments involving CH_3OD as the solvent, anhydrous $NiCl_2$[42] was employed instead of the hexahydrate to avoid complications from exchange processes. The product was analyzed by GC–mass spectrometry, and the ratio of undecane to deuterioundecane was determined by comparison of the relative intensities of the respective parent ions at *m/z* 156 and 157. Values obtained from several cuts of the eluting hydrocarbon were averaged in order to compensate for any fractionation of the deuterated and nondeuterated components.[43] A correction was made for the contribution of the M + 1 peak of undecane to the parent peak of deuterioundecane.

Of 3α-(Phenylthio)cholestane (29). Compound **29** (44 mg, 0.090 mmol) was desulfurized via the general method, using sodium borodeuteride and anhydrous $NiCl_2$ in a 3:1 mixture of CH_3OD and THF. The product was isolated by preparative TLC in hexane to afford 23 mg (69%) of 3α-deuteriocholestane (**30**): R_f 0.76; mp 79–81 °C (lit.[44] mp 80 °C); ^{2}H-NMR δ 1.19 (lit.[20] δ for 3α-deuterioandrostanes: 1.17); mass spectrum (*m/z*, relative intensity) 373 (M^+, 56), 358 (35), 218 (100). The same product **30** was obtained in 48% yield when 3β-chlorocholestane (**28**) (102 mg, 0.250 mmol) in 15 mL of DMF was treated with lithium triethylborodeuteride (1.0 mmol) in THF at reflux overnight.

Of 3β-(Phenylthio)cholestane (26). When compound **26** was desulfurized in the same manner as its 3α-isomer, it produced 3β-deuteriocholestane (**27**) with ^{2}H-NMR δ 1.66 (lit.[20] δ for 3β-deuterioandrostanes: 1.63–1.64) and physical properties otherwise indistinguishable from those of the 3α-isomer **30**. Product **27** was also obtained from the reaction of 3α-chlorocholestane (**25**) with lithium triethylborodeuteride by the procedure described above.

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Supplementary Material Available: Proton NMR spectra of compounds **11**, **12**, **13**, **14**, **15**, and **17** (6 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.

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