Stereochemistry and Mechanism of Catalytic Hydrogenation and Hydrogenolysis. III.*[1] Catalytic Hydrogenolysis of Benzyl-type Alcohols and Their Derivatives*[2]

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In order to obtain evidence for the mechanism we proposed of the catalytic hydrogenolysis of benzyl-type alcohols and their methyl ethers, optically active 2-phenyl-2-butanol (Ia), 2-phenyl-2-methoxybutane (IIa), ethyl atrolactate (Ib), and ethyl 2-phenyl-2-methoxypropionate (IIb) were hydrogenolyzed over Raney nickel and Pd(H) catalysts under hydrogen or helium atmosphere in an ethanol solution. In all cases, the hydrogenolysis proceeded stereoselectively with retention of configuration over Raney nickel catalyst but with inversion of configuration over palladium catalyst. A reverse stereoselectivity was observed when the benzyl alcohols (Ia and 2-phenyl-1,2-dihydroxypropane (Ic)) and methyl ethers (IIa) and (IIb) were hydrogenolyzed in the presence or absence of various additives over nickel catalysts. It was also found that the hydrogenolysis of benzyl alcohols always proceeds with retention of configuration over nickel catalyst containing sodium hydroxide. Various binary mixtures of Ia, IIa, Ib and IIb were hydrogenolyzed competitively over Raney nickel and Pd(H) catalysts. The order of relative rates was found to be Ia$\geq$Ib>IIa$\geq$ IIb over Raney nickel, and IIa$\geq$Ia$\gg$IIb$\geq$Ib over Pd(H) catalyst. The results support our mechanism. The catalytic hydrogenolysis is a competitive reaction of two courses ($S_N i$ type and $S_N 2$ type reactions), and the stereoselectivity reflects the difference of the free energy levels of the transition states to form π-benzylic complexes. The free energy levels of the corresponding transition states depend on stereoelectronic factor, affinity of substituents for catalyst metal, catalyst hindrance and electronic effects of substituents. The acetates (IVa) and (IVb) of Ia and IIa were hydrogenolyzed with inversion of configuration over nickel and palladium catalysts, whereas the stereoselectivity of the hydrogenolysis of the benzoate (V) of IIa depended on the kind of catalyst. The results are also explained on the basis of our mechanism.

We have shown[1] that the catalytic hydrogenolysis of optically active benzyl alcohols and their methyl ethers proceeds stereoselectivity under moderate conditions in an ethanol solution and the stereochemical results are correlated with the nature of the catalyst; the hydrogenolysis proceeds with retention over Raney nickel, cobalt, and copper catalysts but with inversion over palladium and platinum catalysts. From these results, we suggested that the hydrogenolysis proceeds through sterically different chemisorbed states of substrates which depend on the kind of catalyst metal.[1,2]

*[1] Part II: S. Mitsui and S. Imaizumi, This Bulletin, **36**, 855 (1963).

*[2] Part LIII in the series Studies on Hydrogenolysis: Part LII: S. Mitsui, Y. Kudo and M. Kobayashi, Tetrahedron, **25**, 1921 (1969). Presented in part at the 22nd Symposium of Catalysis of the Chemical Society of Japan, Osaka, April, 1968.

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1) a) S. Mitsui, K. Iijima and T. Masuko, Nippon Kagaku Zasshi, **84**, 833 (1963); S. Mitsui and K. Iijima ibid., **85**, 682 (1964). b) S. Imaizumi, ibid., **77**, 1511

(1956); **81**, 627 (1960); S. Mitsui and S. Imaizumi, ibid., **86**, 132 (1965). c) S. Mitsui, S. Imaizumi, I. Takamura and M. Takamura, ibid., **84**, 838 (1963). d) K. Konno and S. Mitsui, ibid., **85**, 497 (1964); Y· Senda and S. Mitsui, ibid., **86**, 229 (1965); S. Mitsui, Y. Senda and K. Konno, Chem. & Ind., **1963**, 1354; S. Mitsui and Y. Kudo, ibid., **1965**, 381; S. Mitsui, Y. Kudo and M. Kobayashi, Tetrahedron, **25**, 1921 (1969). e) S. Mitsui and Y. Nagahisa, Chem. & Ind. (London), **1965**, 1975.

2) S. Mitsui and S. Imaizumi, Nippon Kagaku Zasshi, **77**, 1516 (1956); This Bulletin, **34**, 774 (1961).

Khan, McQuillin and Jardine[3] proposed a mechanism different from ours in which the reaction proceeds *via* the same intermediate(A) over any

X=H or CH$_3$
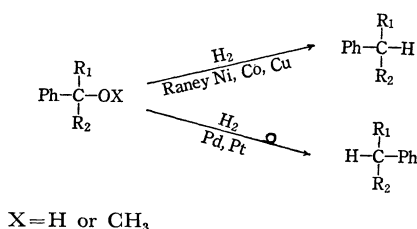
catalyst metal, followed by hydrogen transfer with retention or inversion of configuration depending on the chemical nature of catalyst metal. They considered that nickel-carbon bond is displaced by hydrogen with retention(1), but palladium-carbon bond is displaced by hydrogen in a type of nucleophilic substitution with inversion (2), since the hydrogen supply could be critical by the faster hydrogenolysis over palladium than over nickel and because of the polarization of palladium-carbon bond. Garbisch, Jr., *et al.* offered a mechanism of the hydrogenolysis. However, no detailed process of the formation of inversed product was given.[4]
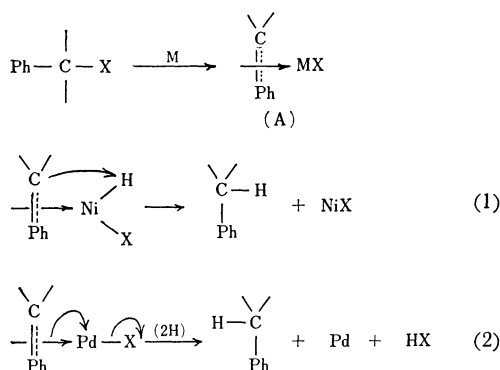
The purpose of the present study is to make a more detailed examination of the hydrogenolysis of optically active benzyl alcohols and their methyl ethers over nickel and palladium catalysts under various conditions, and to improve the mechanism from the results of this study.

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3) A. M. Khan, F. J. McQuillin and I. Jardine, *Tetrahedron Lett.*, **1966**, 2649; *J. Chem. Soc., C*, **1967**, 136.

4) E. W. Garbisch, Jr., L. Schreader and J. J. Frankel, *J. Amer. Chem. Soc.*, **89**, 4233 (1967).

Results

Catalysts. W-4 Raney nickel, "reduced nickel," 5% palladium on charcoal, Raney palladium, and "palladium hydride[5]" were used as catalysts.

The reduced nickel catalyst was prepared by reduction of finely powdered nickel oxide with hydrogen stream at about 300°C. It seems likely that no alkaline substances are contained in the catalyst, since the nickel oxide for the starting material was prepared by thermal decomposition of nickel nitrate.

The palladium hydride catalyst was prepared as follows: An aqueous solution of palladium chloride (5 per cent) was reduced with hydrogen. The metal formed was washed with water until free from chloride ion. The palladium was oxidized for one hour at 400—500°C in atmosphere and then the resulting oxide was reduced by hydrogen in an ethanol suspension. Oxidation and reduction were repeated several times until the volume of consumed hydrogen became nearly constant. The oxide consumed a greater amount of hydrogen than necessary for reduction to metal. It may be assumed that about 80 per cent of palladium was converted into palladium hydride, if all of the occluded hydrogen was consumed to form hydride. The symbols Pd(H) and Pd(H$_{0.4}$) will be used to denote the above catalyst and palladium respectively which occludes 40 per cent of the calculated amount of hydrogen corresponding to PdH.

Hydrogenolysis of Benzyl Alcohols and Their Methyl Ethers. The ethanol solution of optically active 2-phenyl-2-butanol (Ia), 1-phenyl-2-methoxybutane (IIa), ethyl atrolactate (Ib), and ethyl 2-phenyl-2-methoxypropionate (IIb) was hydrogenolyzed to 2-phenylbutane (IIIa) and ethyl 2-phenylpropionate (IIIb), respectively, over Raney nickel, Pd(H) and Pd(H$_{0.4}$) under various conditions. The results are summarized in Tables 1 and 2. In all cases, the hydrogenolysis proceeded stereoselectively with retention of configuration over Raney nickel catalyst but with inversion of configuration over palladium catalyst, the results being the same as those reported on hydrogenolysis using other palladium catalyst under ordinary reaction conditions. It is to be noted that the stereoselective inversion occurred in the hydrogenolysis over Pd(H) and Pd(H$_{0.4}$) but the retention was observed over Raney nickel not only under hydrogen atmosphere but also under helium atmosphere.

In the case of Raney nickel catalyst, the stereoselectivity of hydrogenolysis of benzyl alcohols (Ia) and (Ib) remained unaltered by the addition of

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5) R. J. Rennard, Jr., and R. J. Kokes, *J. Phys. Chem.*, **70**, 2543 (1966).

TABLE 1. CATALYTIC HYDROGENOLYSIS OF 2-PHENYL-2-BUTANOL (Ia) AND ITS
METHYL ETHER (IIa) UNDER VARIOUS CONDITIONS[a]

Compd.	Catalyst (g)	Reaction conditions			Product (IIIa)[b]		Configuration of IIIa	
		Atmos-phere	Press. (atm)	Temp. (°C)	$[\alpha]_D$	Optical purity (%)	Reten-tion	Inver-sion
(+)-Ia[c]	Raney Ni, 5	H_2	1	10	+18.4°	65.5	95.5	4.5
(+)-Ia	Raney Ni, 5	He	1	10	+18.5°	65.9	96	4
(+)-Ia	Raney Ni, 5	H_2	75	10	+16.9°	60.2	92	8
(+)-Ia	Raney Ni, 5	H_2	100	120[d]	−2.2°[e]	61.9	93	7
(+)-Ia	Pd(H), 3	H_2	1	10	−17.9°	63.7	5.5	94.5
(+)-Ia	Pd(H), 3	He	1	10	−17.3°	61.6	7	93
(+)-Ia	Pd(H$_{0.4}$), 3	He	1	10	−17.3°	61.6	7	93
(+)-Ia	Pd(H), 3	H_2	75	10	−16.5°	58.8	9	91
(−)-IIa[f]	Raney Ni, 5	H_2	1	20	−16.5°	58.8	94	6
(−)-IIa	Pd(H), 3	H_2	1	20	+17.1°	60.9	4.5	95.5
(−)-IIa	Pd(H), 3	He	1	20	+17.0°	60.5	5	95
(−)-IIa	Pd(H$_{0.4}$), 3	He	1	20	+17.3°	61.6	4	96

a) Solvent; ethanol 20 ml, reaction time; 10 hr. Under these conditions, Ia and IIa were completely hydrogenolyzed to 2-phenylbutane(IIIa).
b) Solvent; benzene, $c=9.1$. The specific rotation of optically pure S(+)-IIIa is $[\alpha]_D$ +28.1° (benzene).[1a]
c) 0.6 g, $[\alpha]_D^{19}$ +13.2° (neat), optical purity; R(+)-72%.
d) Reaction time; one hr. In this case, the product was 2-cyclohexylbutane (IIIa').
e) This value is the specific rotation of IIIa'. The specific rotation of optically pure S(−)-IIIa' is $[\alpha]_D$ −3.56° (benzene), as shown in experimental section.
f) 0.6 g, $[\alpha]_D^{19}$ −28.6° (neat), optical purity; S(−)-67%.

TABLE 2. CATALYTIC HYDROGENOLYSIS OF ETHYL ATROLACTATE(Ib) AND ITS METHYL
ETHER (IIb) UNDER VARIOUS CONDITIONS[a]

Compd.	Catalyst (g)	Reaction conditions				Conv.[c]	Product (IIIb)[b]		Configuration of IIIb	
		Atmos-phere	Press. (atm)	Temp. (°C)	Time (hr)		$[\alpha]_D$	Optical purity (%)	Reten-tion	Inver-sion
(−)-Ib[d]	Raney Ni, 5	H_2	1	20	48	95	+62.5°	86.6	99	1
(−)-Ib	Raney Ni, 5	He	1	20	48	98	+62.4°	86.4	99	1
(−)-Ib	Raney Ni, 5	H_2	110	20	48	99	+60.2°	83.4	97	3
(−)-Ib	Raney Ni, 5	H_2	2	100	0.5	100	+58.0°	80.3	95.5	4.5
(−)-Ib	Pd(H), 6	H_2	1	20	48	90	−61.0°	84.5	2.5	97.5
(−)-Ib	Pd(H), 6	He	1	20	48	95	−60.7°	84.1	2.5	97.5
(−)-Ib	Pd(H$_{0.4}$), 6	He	1	20	48	91	−57.2°	79.3	5	95
(−)-Ib	Pd(H), 6	H_2	110	20	48	97	−58.1°	80.6	4.5	95.5
(−)-Ib	Pd(H), 6	H_2	1	70	1	93	−59.0°	81.7	4	96
(−)-IIb[e]	Raney Ni, 5	H_2	1	10	50	90	−57.6°	79.8	93.5	6.5
(−)-IIb	Raney Ni, 5	He	1	10	50	89	−60.5°	83.8	96	4
(−)-IIb	Pd(H), 3	H_2	1	10	50	93	+63.0°	87.2	2.5	97.5
(−)-IIb	Pd(H), 3	He	1	10	50	92	+61.8°	85.6	3	97
(−)-IIb	Pd(H$_{0.4}$), 3	He	1	10	50	90	+63.5°	88.0	2	98

a) Solvent: ethanol 20 ml.
b) Solvent: ethanol, $c=9.1$. The specific rotation of the optically pure S(+)-IIIb is $[\alpha]_D$ +72.2° (ethanol).[1b]
c) The product contained a small amount of the cyclohexyl derivatives of IIIb and Ib or IIb.
d) 1.0 g, $[\alpha]_D^{11}$ −24.27° (neat), optical purity, R(−)-88.6%.
e) 0.5 g, $[\alpha]_D^{17}$ −49.50° (neat), optical purity, S(−)-91.5%.

sodium hydroxide. On the other hand, Tables 3 and 4 clearly reveal a decrease in the proportion of the retention of configuration in the cases of methyl ethers (IIa) and (IIb) when the amount of sodium hydroxide added increased. A similar trend in the stereoselectivity was also obtained when alkali halide were added instead of sodium hydroxide.

TABLE 3. CATALYTIC HYDROGENOLYSIS OF 2-PHENYL-2-BUTANOL (Ia) AND ITS METHYL ETHER (IIa) OVER NICKEL CATALYST[a]

Compd.	Catalyst (g)	Additive (mg)	Reaction conditions			Conv. (%)	Product (IIIa)[b]		Configuration of IIIa	
			Press. (atm)	Temp. (°C)	Time (hr)		$[\alpha]_D$	Optical purity (%)	Retention	: Inversion
(+)-Ia[c]	Raney Ni, 5	——	1	10	10	100	+18.4°	65.5	95.5	4.5
(+)-Ia	Raney Ni, 5	NaOH, 400	1	70	20	17	+18.1°	64.7	95	5
(+)-IIa[d]	Raney Ni, 5	——	1	60	120	100	+20.6°	73.3	94	6
(+)-IIa	Raney Ni, 5	NaOH, 80	1	60	120	86	+6.8°	24.2	64.5	35.5
(+)-IIa	Raney Ni, 5	NaOH, 400	1	60	120	42	−10.1°	35.9	28.5	71.5
(−)-IIa[f]	Raney Ni, 5	——	1	60	120	100	−14.3°	50.9	88	12
(−)-IIa	Raney Ni, 5	NaOH, 80	1	60	120	75	−4.0°	14.2	60.5	39.5
(−)-IIa	Raney Ni, 5	NaOH, 400	1	60	120	47	+8.7°	31.0	27	73
(+)-Ia[c]	Ni[e], 2	——	100	120	5	100	−14.4°	51.3	14.5	85.5
(+)-Ia	Ni, 2	——	100	140	5	100	−11.0°	39.2	22.5	77.5
(+)-Ia	Ni, 2	NaOH, 1	100	160	10	100[g]	+19.4°	69.1	98	2
(+)-IIa[d]	Ni, 2	——	100	120	5	100	−7.7°	27.4	33.5	66.5

Notations b, c and f) refer to the footnotes of Table 1.   a) Solvent; ethanol 20 ml.
d) 0.6 g, $[\alpha]_D^{19}$ +35.2° (neat), optical purity; R(+)-83%.   e) "Reduced nickel" catalyst.
g) 2-Cyclohexylbutane(12%), IIIa(38%) and 2-cyclohexyl-2-butanol(50%) were produced.

TABLE 4. CATALYTIC HYDROGENOLYSIS OF ETHYL ATROLACTATE (Ib) AND ITS METHYL ETHER (IIb) AND 2-PHENYL-1,2-DIHYDROXYPROPANE (Ic) OVER NICKEL CATALYST[a]

Compd.	Catalyst (g)	Additive (mg)	Reaction conditions			Conv.[c]	Product (IIIb)[b]		Configuration of IIIb	
			Press. (atm)	Temp. (°C)	Time (hr)		$[\alpha]_D$	Optical purity(%)	Retention	: Inversion
(+)-Ib[d]	Raney Ni, 5	——	1	20	50	98	−65.0°	90.0	99	1
(+)-Ib	Raney Ni, 5	NaOH, 40	1	70	50	30	−65.1°	90.2	99	1
(+)-Ib	Raney Ni, 5	KBr, 119	1	20	150	65	−63.2°	87.6	97.5	2.5
(−)-IIb[e]	Raney Ni, 5	——	1	20	50	95	−59.4°	82.3	95	5
(−)-IIb	Raney Ni, 5	NaOH, 40	1	20	50	94	+20.1°	27.8	35	65
(−)-IIb	Raney Ni, 5	NaOH, 80	1	20	50	77	+30.1°	41.7	27	73
(−)-IIb	Raney Ni, 5	NaCl, 58	1	20	50	70	−53.9°	74.7	91	9
(−)-IIb	Raney Ni, 5	NaBr, 103	1	20	150	72	−36.7°	50.8	78	22
(−)-IIb	Raney Ni, 5	KCl, 75	1	20	150	69	−35.9°	47.9	77	23
(−)-IIb	Raney Ni, 5	KBr, 119	1	20	150	61	+10.6°	14.7	42	58
(+)-Ib[d]	Ni[f], 2	——	100	110	70	58	−47.0°	65.1	85.5	14.5
(+)-Ib	Ni, 2	——	100	140	40	64	−48.6°	67.3	86.5	13.5
(+)-Ib	Ni, 2	KBr, 6	100	170	95	30	−24.0°	33.2	68	32
(+)-Ic[g]	Raney Ni, 5	——	1	20	10	100[h]	+15.0°[i]	83.3	99.5	0.5
(+)-Ic	Ni[f], 2	——	100	130	30	100[h]	−13.2°[i]	73.4	6.5	93.5

Notations a-c) refer to the footnotes of Table 2.
d) 1.0 g, $[\alpha]_D^{20}$ +25.16° (neat), optical purity; S(+)-91.9%.
e) 1.0 g, $[\alpha]_D^{17}$ −49.50° (neat), optical purity; S(−)-91.5%.
f) "Reduced nickel" catalyst.
g) 0.5 g, $[\alpha]_D^{16}$ +5.1° (c, 1.96, ethanol), optical purity; S(+)-84%.
h) 2-Phenyl-1-propanol(Ic).
i) Solvent: benzene, c=9.1. The specific rotation of the optically pure R(+)-Ic is $[\alpha]_D$ +18.0° (benzene).[1b]

In order to see why the benzyl alcohols were hydrogenolyzed with retension of configuration over Raney nickel catalyst in any reaction conditions, "reduced nickel" was used as nickel catalyst which contains no alkaline substance. Hydrogenolysis proceeded only at elevated temperature, and stereoselectivity depended on the structure of benzyl alcohols as shown in Tables 3 and 4. Hydrogenolysis proceeded with predominantly retention of configuration in the case of Ib, but with predominantly inversion of configuration in the cases of Ia, IIa and 2-phenyl-1,2-dihydroxypropane (Ic). Ia was hydrogenolyzed with retention of configuration under the conditions where a trace amount of sodium hydroxide is present (Table 3).

These results suggest that the stereoselectivity of hydrogenolysis of benzyl alcohols and their methyl ethers over nickel catalyst is correlated with the structure of substrates, the kind of nickel catalyst and additives, and that an alkaline substance which is contained inevitably over Raney nickel catalyst acts as an effective factor in the stereospecific hydrogenolysis of benzyl alcohols with retention of configuration.

Competitive Hydrogenolysis of the Benzyl Alcohols(Ia) and (Ib) and Their Methyl Ethers (IIa) and (IIb).

The order of relative rates of hydrogenolysis of the substrates was found to be Ia$\geq$Ib>IIa$\geq$IIb over Raney nickel catalyst, and IIa$\geq$Ia$\gg$IIb$\geq$Ib over Pd(H) catalyst at room temperature and atmospheric pressure in an ethanol solution. Various binary mixtures of Ia, Ib, IIa and IIb were hydrogenolyzed competitively over both catalysts under the same condition as in individual hydrogenolysis. The results are summarized in Table 5. The competitive rates in hydrogenolysis of the binary mixture of

Ia and Ib were similar over Raney nickel catalyst, whereas Ia was more rapidly hydrogenolyzed than Ib over Pd(H) catalyst. In the case of the binary mixture of Ib and IIb, Ib reacted more readily than IIb over Raney nickel catalyst, while a reverse relation was observed over Pd(H) catalyst. The same competitive rates were observed in the binary mixtures of IIa and IIb, and Ia and II a,respectively.

Hydrogenolysis of Benzyl Acetates and Benzoates.

The ethanol solution of optically active 2-phenyl-2-acetoxybutane (IVa), ethyl 2-phenyl-2-acetoxypropionate (IVb), and ethyl 2-phenyl-2-benzoyloxypropionate (V) was hydrogenolysed to IIIa and IIIb, respectively, over Raney nickel, reduced nickel, 5% palladium on charcoal, Pd(H), and Raney palladium catalysts under various conditions. The results are summarized in Table 4. The hydrogenolysis of the acetates (IVa) and (IVb) proceeded with inversion of configuration under all reaction conditions. Hydrogenolysis of the benzoate (V) proceeded predominantly with retention of the configuration over Pd(H) catalyst, while the reverse stereoselectivity was observed over palladium on charcoal, Raney palladium and Raney nickel catalysts.

$$\begin{array}{ccc} CH_3 & & CH_3 \\ | & & | \\ Ph-C-OX & \longrightarrow & Ph-C-H \\ | & & | \\ R & & R \end{array}$$

Ia: R=C$_2$H$_5$, X=H   IIIa: R=C$_2$H$_5$
Ib: R=COOC$_2$H$_5$, X=H   IIIb: R=COOC$_2$H$_5$
Ic: R=CH$_2$OH, X=H   IIIc: R=CH$_2$OH
IIa: R=C$_2$H$_5$, X=CH$_3$
IIb: R=COOC$_2$H$_5$, X=CH$_3$
IVa: R=C$_2$H$_5$, X=COCH$_3$
IVb: R=COOC$_2$H$_5$, X=COCH$_3$
V: R=COOC$_2$H$_5$, X=COPh

Discussion

Mechanism of the Hydrogenolysis of Benzyl-type Alcohols and Their Methyl Ethers.

Khan *et al.* considered that the hydrogenolysis of benzyl alcohols and their methyl ethers over palladium catalyst proceeds with the inversion of configuration, since the hydrogen supply could be critical by rapid hydrogenolysis, *i.e.*, the intermediate (A) reacts with hydrogen from the opposite side of the catalyst surface by a deficiency of adsorbed hydrogen.[3] This prompted us to investigate the hydrogenolysis under various reaction conditions, especially over Pd(H) under helium atmosphere.

The results summarized in Tables 1 and 2 show that the stereoselectivity is independent of the kind of atmosphere. Thus, the hydrogenolysis over Pd(H) and Pd(H$_{0.4}$) proceeded with the stereo-

TABLE 5. COMPETITIVE HYDROGENOLYSIS OF VARIOUS BINARY MIXTURES OF BENZYL ALCOHOLS(Ia AND Ib) AND THEIR METHYL ETHERS(IIa AND IIb) UNDER ATMOSPHERIC PRESSURE AND ROOM TEMPERATURE

Compounds[a]	Catalyst[b]	Competitive rate of hydrogenolysis[c]	
Ia+Ib	Raney Ni	Ia=1.4	Ib=1.2
Ia+Ib	Pd(H)	Ia=50	Ib=0.1
IIa+IIb	Raney Ni	IIa=0.2	IIb=0.1
IIa+IIb	Pd(H)	IIa=53	IIb=0.1
Ia+IIa	Raney Ni	Ia=2.0	IIa=0.2
Ia+IIa	Pd(H)	Ia=33	IIa=36
Ib+IIb	Raney Ni	Ib=1.5	IIb=0.1
Ib+IIb	Pd(H)	Ib=0.2	IIb=0.5

a) The concentration of each substrate was approximately 0.2 molar ethanol solution (10 m*l*).
b) Raney Ni; 1 g (wet). Pd(H); 1 g.
c) Initial rate (at 20°C); ×10^{-4} mol/hr.

TABLE 6. CATALYTIC HYDROGENOLYSIS OF 2-PHENYL-2-ACETOXYBUTANE (IVa), ETHYL 2-PHENYL-2-
ACETOXYPROPIONATE (IVb) AND 2-PHENYL-2-BENZOYLOXYPROPIONATE (V) OVER NICKEL
AND PALLADIUM CATALYSTS[a]

| Compd. | Catalyst | Reaction condition | | | | Product (III)[b] | | Configuration of III | |
		Press. (atm)	Temp. (°C)	Time (hr)	Conv. (%)	$[\alpha]_D$	Optical purity (%)	Reten- tion	Inver- sion
(+)-IVa[c]	Raney Ni, 5	1	20	48	60	−16.9°	60.1	8	92
(+)-IVa	Raney Ni, 5[d]	1	20	1	100	−18.9°	67.3	3	97
(+)-IVa	Ni[e], 2	100	50	10	60	−19.4°	69.1	2	98
(+)-IVa	5%Pd-C, 0.5	1	20	4	100	−16.9°	60.1	8	92
(+)-IVa	Pd(H), 3	1	20	0.1	100	−16.9°	60.1	8	92
(+)-IVa	Pd(H), 3	1[f]	20	0.5	100	−18.2°	64.9	5	95
(−)-IVb[g]	Raney Ni, 10	1	20	72	50	+43.2°	59.8	16.5	83.5
(−)-IVb[h]	Raney Ni, 10[d]	1	20	6	100	+54.4°	75.3	9	91
(−)-IVb	Ni[e], 2	100	140	15	98	+59.4°	82.3	5	95
(−)-IVb	5%Pd-C, 0.5	1	20	24	100	+58.1°	80.5	6	94
(−)-IVb	Pd(H), 3	1	20	15	100	+59.4°	82.3	5	95
(−)-IVb	Pd(H$_{0.4}$), 3	1[f]	20	15	100	+60.7°	84.1	4	96
(+)-V[g]	Raney Ni, 10	1	20	48	80	+23.9°	33.1	31.5	68.5
(+)-V[i]	Raney Ni, 10[d]	1	20	4	100	+45.3°	62.5	15	85
(+)-V[j]	Raney Pd, 0.5	1	20	30	80	+49.7°	68.8	12.5	87.5
(+)-V	5%Pd-C, 5	1	20	10	90	+15.3°	21.2	38.5	61.5
(+)-V	Pd(H), 6	1	20	30	90	−24.2°	33.5	67	33
(+)-V	Pd(H), 3	1	20	50	60	−15.4°	21.3	61.5	38.5
(+)-V	Pd(H), 3	1	70	8	95	−35.0°	48.5	76.5	23.5

a) Substrate; 0.005 mol, solvent; ethanol 20 ml.
b) The optically pure rotations of IIIa and IIIb refer to foot note b) of Tables 1 and 2, respectively.
c) α_D^{20} +1.12 (neat, $l=1$), optical purity; R(+)-72%.
d) Sodium hydroxide (0.005 mol) was added.
e) " Reduced nickel " catalyst.
f) Atmosphere: helium.
g) Ref. 12. Optical purity; 89.1%.
h) $[\alpha]_D^{20}$ −31.7° (c 9.1, ethanol), optical purity; S(−)-91.9%.
i) Ref. 1c. Optical purity; 89.1%.
j) $[\alpha]_D^{20}$ +34.6° (c 9.1, ethanol), optical purity; S(+)-91.9%.

specific inversion of configuration not only under hydrogen atmosphere but also under helium atmosphere, in which no hydrogen is detected by means of vapor phase chromatographic analysis in the gas phase during the reaction. These results suggest that the hydrogen which takes part in the hydrogenolysis attackes an adsorbed substrate from the side of catalyst surface. Thus, the results are not in line with the consideration of Khan et al.,[3] but support our mechanism.[1,2]

It seems that the hydrogenolysis proceeds through π-adsorption of the phenyl group, followed by the formation of a π-benzylic complex with the catalyst. This complex formation will be similar to that of a π-allylic complex with transition-metal catalysts. In the transition state, thus, there is a change toward sp²-hybridization at the benzylic carbon with the carbon-oxygen bond becoming labile. The leaving group is finally eliminated by

combination with surface hydrogen π-benzylic complex being formed.[6]

From the results, the mechanism of hydrogenolysis of benzyl-type alcohols (I) and their methyl ethers (II) may be described as follows: The substrate (B) is adsorbed over the catalyst surface. An electron attacks nucleophilically the adsorbed substrates (C) and (D) from the surface of the catalyst, and then π-benzylic intermediates (G) and (H) are produced through transition states (E) and (F), respectively. The resulting intermediates (G) and (H) decompose to the adsorbed products

6) J. J. Rooney, F. G. Gault and C. Kemball, Proc. Chem. Soc., 1960, 407; F. G. Gault, J. J. Rooney and C. Kemball, J. Catal., 1, 255 (1962); J. J. Rooney, ibid., 2, 53 (1963); J. J. Rooney and G. Webb, ibid., 3, 488 (1964); J. J. Rooney, Chem. Brit., 2, 242 (1966).

(B) → (C) ⇌ (E)‡ → (G) → (J) (3)

(B) → (D) ⇌ (F)‡ → (H) → (K) (4)
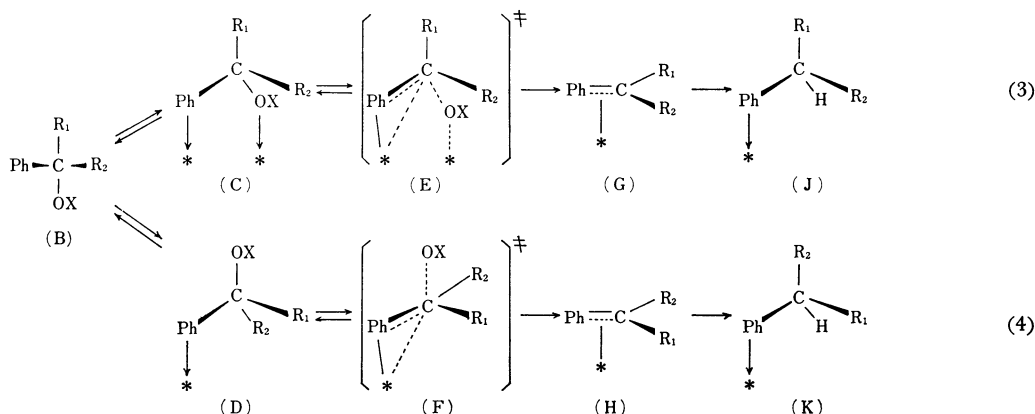
(J) and (K) by hydrogen from the surface of the catalyst with retention of configuration.

The intermediates (G) and (H) are identical in the half-hydrogenated state in the catalytic hydrogenation of styrene derivatives.[7] It has been reported that the intermediate readily decomposes to the adsorbed product by hydrogen from the catalyst surface with the retention of configuration not only over nickel catalyst but also over palladium catalyst.[7] Therefore, it seems that the stereoselectivity of hydrogenolysis is not determined by the step of the decomposition of the intermediates (G) and (H) with hydrogen.

The fact that the hydrogenolysis of I and II over palladium catalyst proceeds with the stereoselective inversion of configuration under all reaction conditions (Tables 1 and 2), suggests that the stereoselectivity is not determined by the step of the adsorption of the substrate in the mechanism. It is unlikely that both Ia and Ib are adsorbed only in one form (D) over palladium catalyst.

Therefore, the stereoselectivity over palladium catalysts may be determined by the difference in the free-energy levels of the transition states (E) and (F) to form π-benzylic complexes in the two courses (Reactions (3) and (4)), since the above results suggest that the activation energies for the cleavage of carbon-oxygen bond (C→G, and D→H) is larger than that for the adsorption of the substrate (B→C, and B→D) and that for the decomposition of carbon-metal bond of the π-benzylic complex to the adsorbed products (G→J, and H→K).

The mechanism is supported by the results of hydrogenolysis of the benzyl alcohol derivatives such as *cis*- and *trans*-1-phenylcyclohexane-1,2-diol, their monoacetates and diacetates, containing an eliminable substituents in β-position.[8]

The results of the palladium catalyzed hydrogenolysis of I and II suggest that the free energy of transition state (F) is lower than that of (E). This may be due to the fact that reaction (4) in which an electron attacks nucleophilically the asymmetric carbon from the opposite side of the leaving hydroxyl or methoxyl groups, *i.e.*, from the catalyst surface, (S_N2 type reaction on catalyst) has an advantage of fulfilling the stereoelectrical requirement in contrast with reaction (2) in which the leaving group is displaced in the same side (S_Ni type reaction on catalyst) in the same way as in homogeneous nucleophilic substitution reaction on carbon.

In the case of Raney nickel catalyst, the hydrogenolysis of I and II proceeds with the retention of configuration. Thus, the fact that the course of reaction (3) is preferable to that of reaction (4) may be due to the strong affinity of the leaving group for Raney nickel catalyst. It is well known that nickel has a strong affinity for oxygen.[9] Accordingly, Raney nickel may adsorb the groups containing oxygen more than palladium. Thus the free enrgy level of the transition state(E) may be lower than that of (F), since the strong chemisorption of the sterically small leaving groups, such as hydroxyl or methoxyl, decreases not only free energy level of adsorption state(C) but also the activation energy from (C) to intermediate(G).

The Effect of Additives over Nickel Catalysts. It was reported that the stereoselectivity of hydrogenolysis of the phenyl ether[10] of Ib and epoxides[1e,11] depended on the presence or ab-

7) G. V. Smith and J. A. Roth, *J. Amer. Chem. Soc.*, **88**, 3879 (1966); S. Mitsui, Y. Nagahisa, K. Tomomura and S. Shionoya, *Shokubai*, **10**, Preprint of 23rd Symposium on Catalysis, 74p (1968).

8) S. Mitsui, M. Fujimoto, Y. Nagahisa and T. Sukegawa, *Chem. & Ind.*, **1969**, 241; *Kogyo Kagaku Zasshi*, **73**, 97 (1970).

9) For example, K. Tanaka and K. Tamaru, *J. Catal.*, **2**, 366 (1963).

10) S. Mitsui and S. Imaizumi, This Bulletin, **36**, 855 (1963); *Kogyo Kagaku Zasshi*, **68**, 816 (1965).

sence of an additive over catalyst. However, the effect of an additive for I and II has not been studied. The mechanism presented here suggests that the reverse stereoselectivity may also be observed over nickel catalyst if the hydrogenolysis of I and II carried out under the reaction conditions which weaken the adsorption of substrate over the catalyst. In fact, the reverse stereoselectivity was observed under several reaction conditions as seen in Tables 3 and 4. Thus, the inversed product is produced predominantly by the addition of sodium hydroxide or alkali halides over Raney nickel catalyst in the hydrogenolysis of methyl ethers (IIa) and (IIb). The results may be expalined by assuming that the additives act as a catalyst poison which weakens the adsorption of substrate over the catalyst. Then the course of reaction (4) will become more advantageous to that of reaction (3) over the poisoned nickel catalyst, since hydrogenolysis may be retarded by the additives, especially in (3) which needs a strong adsorption of the leaving group.

On the other hand, the stereoselectivity of hydrogenolysis of benzyl alcohols over Raney nickel catalyst is not affected by the additives. The divergent result can be ascribed to the effect of alkaline substance contained inevitably in Raney nickel catalyst, because the inversed product is formed predominantly in the hydrogenolysis of Ia over reduced nickel catalyst but the retained product is produced in the presence of sodium hydroxide over the same catalyst (Table 3). Benzyl alcohols differ from their methyl ethers in having free hydroxyl group, and in forming their alkoxide anions with alkali over the catalyst. Therefore, the reaction of course (4) is disfavored by the decrease of the electronegativity of the leaving group, i.e., by the resonance effect of the anion, resulting in the selective hydrogenolysis through course (3).

As seen in Table 3, methyl ether (IIa) was hydrogenolyzed with the inversion of configuration over the reduced nickel catalyst in contrast to the case over Raney nickel catalyst. However, it is clear that the activity of the reduced nickel catalyst is lower than that of Raney nickel catalyst because the former acts as a hydrogenolysis catalyst only at an elevated temperature. It is likely from these results that the reduced nickel behaves like the catalyst poisoned with substances other than alkali. Thus, it is assumed that the hydrogenolysis of Ia proceeds predominantly with the inversion of configuration over the reduced nickel catalyst similar to the case of IIa. It is evident that alkali acts as an effective factor for the stereoselectivity of the hydrogenolysis of benzyl alcohols because Ia is

hydrogenolyzed with retention of configuration in the presence of sodium hydroxide over the reduced nickel catalyst. The result may be explained from the formation of the alkoxide anions of the benzyl alcohols with alkali over the catalyst as described before. A similar effect of sodium hydroxide has been observed in the hydrogenolysis of 2-methyl-2-phenylazilidine over palladium catalyst.[12]

In the case of ethyl atrolactate (Ib), hydrogenolysis proceeded predominantly with the retention of configuration over the reduced nickel catalyst, but the stereoselectivity was low compared with the case of Raney nickel catalyst, and decreased by the addition of potassium bromide (Table 4). Thus, it is clear that the tendency of variation of stereoselectivity is similar to that observed in the case of Ia, but the degree of variation is slight. It appears to depend on the structure of benzyl alcohols. The structure of Ib differs from that of Ia only in having the ethoxycarbonyl group instead of the ethyl group. It is clear that the bulkiness and electronegativity of the ethoxycarbonyl group are greater than those of the ethyl group, and that if the reaction proceeds via course (4), the ethoxycarbonyl group of Ib must be placed to the side of the catalyst surface, whereas the ethoxycarbonyl group in the reaction via course (3) may or may not be placed thus. The results suggest that the effect of the catalyst hindrance of the ethoxycarbonyl is larger than the electronic effect in its adsorbed state for the hydrogenolysis of Ib.

This consideration is in line with the results of the competitive hydrogenolysis of various binary mixtures of the substrates (Ia, Ib, IIa and IIb), i.e., as shown in Table 5, Ia and IIa are more rapidly hydrogenolyzed than Ib and IIb, respectively, over Pd(H) catalyst, in which the hydrogenolysis proceeds with the inversion of the configuration, whereas similar rates were observed in the case of Raney nickel catalyst, in which the hydrogenolysis proceeds with the retention of the configuration.

The consideration is supported by the fact that the hydrogenolysis of 2-phenyl-1,2-dihydroxypropane (Ic) which had sterically smaller methylol group than ethoxycarbonyl group of Ib proceeds with the inversion of the configuration over reduced nickel catalyst (Table 4), similarly as in Ia.

The results led us to the conclusion that the stereoselectivity of the catalytic hydrogenolysis of benzyl alcohols and their methyl ethers depends on the difference in the free energy levels of the transition states (E) and (F). The free energy levels of E and F depend on such factors as stereoelectronic factor, affinity of substituents for catalyst metal, catalyst hindrance, and electronic effects

11) S. Mitsui and S. Imaizumi, Nippon Kagaku Zasshi, 86, 219 (1965).

12) S. Mitsui and Y. Sugi, Tetrahedron Lett., 1969, 1291; This Bulletin, 43, 1489 (1970).

of substituents.

Hydrogenolysis of Benzyl Acetates and Benzoates.

Let us consider the stereochemistry of the hydrogenolysis of other derivatives of benzyl alcohols.

The hydrogenolysis of the acetates (IVa) and (IVb) proceeded with the inversion of configuration under all reaction conditions (Table 6), the results being the same as those reported in the hydrogenolysis of IVb[13] and of other benzyl acetates.[3,4,14] The stereoselectivity of hydrogenolysis of benzoate (V) depended on the kind of catalyst.

The results of benzoate(V) cannot be explained by the consideration of Khan et al.[3] that hydrogenolysis of the benzyl derivatives, such as acetate and benzoate, having a strongly electronegative leaving group proceeds with the inversion of configuration via course (2). These results may be also explained on the basis of our mechanism of the hydrogenolysis of I and II.

The fact that the acetates are hydrogenolyzed with the stereospecific inversion of configuration over both nickel and palladium catalyst suggests clearly that stereoselectivity is not determined by the difference of the step to form the adsorption states (C and D), since the acetoxyl and ethoxy-carbonyl groups may be adsorbed with greater facility over the catalyst than the alkyl group. Thus, stereoselectivity may be correlated with the difference in the free energy levels of the transition states (E) and (F) to form the π-benzyl intermediates (G) and (H), in analogy with the cases of hydrogenolysis of I and II.

It is considered that $S_N 2$ type reaction on catalyst in the hydrogenolysis of benzyl acetates proceeds with greater facility than that of benzyl alcohols and their methyl ethers, because the acetoxyl group of the acetates has a strong electron attractive nature. It seems likely therefore, that the hydrogenolysis of benzyl acetates proceeds generally with the inversion of configuration via course (4) under all reaction conditions.

The stereoselectivity of hydrogenolysis of benzoate (V) depended on the reaction conditions (Table 6). Thus, the hydrogenolysis proceeded predominantly with the retention of configuration over Pd(H) catalyst, but the reverse stereoselectivity was observed over palladium on charcoal, Raney palladium and Raney nickel catalysts.

These results suggest that the difference of the activation energy between the two courses (3) and (4) for V is smaller than that for the acetate(IVb). Although the benzoyloxyl group of V unquestionably

possesses a stronger affinity with the catalyst and a larger catalyst hindrance than those of the acetoxyl group of IVb, the effect of the former may be larger for the hydrogenolysis of V, compared with the case of IVb, because both the carbonyl and the phenyl of the benzoyloxyl group are π-adsorbed. These effects are similar to those of the phenyl group of the phenyl ether of Ib.[10] Thus, the strong chemisorption of the benzoyloxyl group is expected to facilitate course (3) in line with the hydrogenolysis of I and II over Raney nickel catalyst. Consequently, differing from the case of acetates (IV) the stereoselectivity of hydrogenolysis of V may depend on the reaction conditions.

When a catalyst which has many suitable pores such as Raney catalyst is used, hydrogenolysis with an inversion of configuration over two phases of the catalyst surface cannot be ruled out, in analogy with the hydrogenolysis of phenyl ether[10] of Ib, since the benzoyloxyl group has a planar structure containing π-electrons, and asymmetric carbon-oxygen bond of the substrate is able to rotate freely. It is assumed that the reaction via this adsorption state has a smaller activation energy than that via the other adsorption states. Needless to say, this reaction course is included in course (4).

When the benzoyloxyl and phenyl groups of the benzoate(V) are adsorbed strongly over the catalyst, partial participation of the radical cleavage reaction on catalyst is made possible, giving a racemic product.[2,13] These factors may further complicate the stereoselectivity of hydrogenolysis of V.

Recently a similar variable stereoselectivity has been also found in the Raney nickel catalyzed desulfuration of benzylsulfone derivatives by Grimm and Bonner.[15] It is assumed that desulfuration, in analogy with the hydrogenolysis of the benzoate, may be also complicated by the participation of many reaction courses which depend on the structure of substrate and reaction conditions.

Experimental

Materials. All compounds used in this study have been previously reported; R(+)-2-phenyl-2-butanol (Ia),[1a] $[\alpha]_D^{19} +13.2°$ (neat), 72% optical purity; S(−)-2-phenyl-2-methoxybutane(IIa)[1a], $[\alpha]_D^{19} -28.6°$ (neat), 67% optical purity; R(+)-2-phenyl-2-acetoxybutane (IVa),[16] $\alpha_D^{20} +1.12°$ (neat, $l=1$), 72% optical purity; ethyl R(−)-atrolactate(Ib),[1b] $[\alpha]_D^{11} -24.27°$ (neat), 88.6% optical purity; ethyl S(−)-2-phenyl-2-methoxy-propionate (IIb),[1b] $[\alpha]_D^{17} -49.50°$ (neat), 91.5% optical purity; ethyl S(−)-2-phenyl-2-acetoxypropionate (IVb),[13] $[\alpha]_D^{20} -31.7°$ (c 9.1, ethanol), 91.9% optical purity; ethyl S(+)-2-phenyl-2-benzoyloxypropionate

13) S. Imaizumi, *Nippon Kagaku Zasshi*, **81**, 631 (1965).

14) F. G. Bordwell and E. W. Garbisch, Jr., *J. Org. Chem.*, **28**, 1765 (1963).

15) R. A. Grimm and W. A. Bonner, *ibid.*, **32**, 3470 (1967).

16) D. J. Cram, *J. Amer. Chem. Soc.*, **74**, 2149 (1952).

(V),[13] $[\alpha]_D^{20}+34.6°$ (c 9.1, ethanol), 91.9% optical purity; S(+)-2-phenyl-1,2-dihydroxypropane(Ic),[1b] $[\alpha]_D^{16}+5.1°$ (c 1.96, ethanol), 84% optical purity.

Hydrogenolysis. Hydrogenolysis was carried out in 20 ml of ethanol containing a known amount of substrate, catalyst and additive. The catalyst was filtered. In the cases of Ia, IIa and IVa, 200 ml of water was added to the filtrate, and then extracted with ether. The ether layer was washed with a saturated sodium bicarbonate solution and was dried over anhydrous calcium chloride, and the solvent was removed. 2-Phenylbutane (IIIa) was then separated from the residual oil by distillation (bp 60°C/15 mmHg) or by vapor phase chromatography (2 m of column packed with a polyethylene glycol-4000 on 30—60 mesh firebrick). In the cases of Ib and IIb, the solvent was distilled, and ethyl 2-phenylpropionate (IIIb) was then separated from the residual oil by vapor phase chromatography. In the cases of IVb and V, the solvent was distilled. The residual oil was taken up in ether and extracted with a saturated sodium bicarbonate solution. The alkaline insoluble material was dried over anhydrous sodium sulfate, and the solvent removed. IIIb was then separated from the residual oil by vapor phase chromatography. In the case of Ic, the solvent was distilled. The residual oil was distilled at reduced pressure to give 2-phenyl-1-propanol (IIIc), bp 120°C/21 mmHg.

The stereochemical results are shown in Tables 1, 2, 3, 4, and 6.

Competitive Hydrogenolysis. Hydrogenolysis was carried out with each of the individual substrates and their various binary mixtures under atmospheric pressure and at room temperature (20°C). For the hydrogenolysis of the individual substrates, 10 ml of ethanol and 0.004 mol of the substrate were used. Hydrogenolysis of the binary mixtures of the substrates was carried out with an ethanol solution (10 ml) of the two substrates concerned. The concentration of each substrate was approximately 0.2 molar. Catalyst weights were 1 g of Raney nickel (wet) and 1 g of Pd (H) for each run. Small amounts of samples were extracted through a silicone rubber stopper with a hypodermic syringe at suitable intervals and analyzed by glcp procedures (45 m Golay column coated with polyethylene glycol-4000). The results are shown in Table 5.

2-Cyclohexylbutane (IIIa'). R(−)-2-Phenylbutane ($[\alpha]_D^{21}-15.4°$ (benzene), optical purity 54.8%) was hydrogenated over platinum catalyst in ethanol under hydrogen at an ordinary temperature and pressure until the hydrogen was no longer adsorbed. The catalyst was filtered and rinsed with ether. Water and ether were added to the filtrate, and ether layer was dried over anhydrous calcium chloride, and then the solvent was removed. The residual oil distilled at reduced pressure gave R(+)-2-cyclohexylbutane (IIIa'), bp 60°C/ 15 mmHg, $[\alpha]_D^{25}+1.95°$ (benzene). The specific rotation of the optically pure IIIa' is calculated to be $[\alpha]_D$ 3.56° (benzene).