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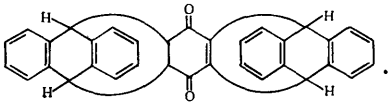
STEREOCHEMISTRY OF HYDROGENATION AND HYDROGENOLYSIS

E.I. Klabunovskii

Optically active compounds and compounds whose molecules have a rigid three-dimensional configuration may prove extremely useful in the study of the mechanism of catalysis and the structure of the active surface of catalysts. The advantages of catalytic studies of this kind arise because the initial molecules has a definite well known configuration and it is possible to construct stereochemical models for the intermediate complexes, to follow the stereochemical reaction pathways, and to obtain information about the structure of the active surface of the catalyst.

Such studies are being made both to investigate the geometry of the catalyst surface, using reactions of molecules with a complex three-dimensional structure, and to elucidate the configurational and energy interactions between the groups of the optically active compounds adsorbed on the surface.

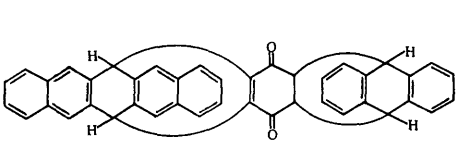
The first approach to the study of the active surface of catalysts has been achieved by hydrogenating triptycene derivatives[1] such as 2,3(9,10-anthrylene)-5,6-(9,10-anthrylene)-2-cyclohexene-1,4-dione (I), for example:



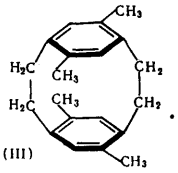
(I)

The hydrogenation of the C=C bond in the central ring of this compound occurs at an appreciable rate on a nickel catalyst even at 45°.[1] The preservation of the rigid structure of the molecule during the catalytic process, which excludes any appreciable deformation or reversal of the configuration by an S_N2 mechanism, makes it possible to construct stereochemical models of the active centre. Since chemical valence forces are of short range, the molecules are in contact with the catalyst via the reacting C=C atoms, which determines the orientation of the molecule during catalysis. The edgewise orientation on the surface is excluded in this case by the structure of the molecule and therefore it is necessary to postulate a planar disposition of the central ring on the (111) plane of the nickel crystal. Since the molecule has a complex three-dimensional structure, it cannot lie flat on this plane and it must be assumed that the correct orientation of such a molecule on the centre requires a projecting centre bounded by the (111) plane and adjacent to a number of "hollows" where the non-reacting parts of the molecules are located. On the basis of the actual dimensions of the molecular model, the height of the projecting centre in an optimum catalyst of this kind must be not less than 4.30 Å.

On catalysts with both "rougher" and more "even" surfaces the reaction of such a compound is hindered because of the reduced probability of occurrence on the surface of centres corresponding to the structure of the reacting molecule. Equally, the reaction rate may be reduced also because of an increase in "catalytic difficulties" as a result of an increase in the complexity of the three-dimensional structure of the molecule, for example when instead of compound (I) compound (II) is hydrogenated:

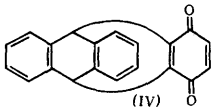


(II)

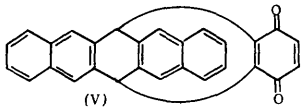


(III)

It is interesting that tetramethyl[2,2]paracyclophane (III)[2] is not hydrogenated at the usual temperature and pressure on 10% Pd/C catalysts or PtO_2. In the general case breakdown of the coplanarity of the molecule hinders hydrogenation. However, when the non-coplanar part of the molecule is not in immediate contact with the catalyst, as, for example, in the hydrogenation of triptycenequinone (IV) and dibenzotriptycenequinone (V), the rates of hydrogenation (1 atm, 45°) are almost indistinguishable[3].

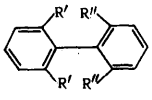


(IV)

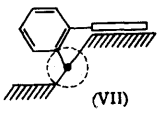


(V)

The structure of the molecule is the decisive factor in the catalytic reaction and when the structure is sufficiently complex and rigid, preventing the contact of the molecule with the active catalyst surface, the reaction cannot be achieved. For example, the biphenyl derivatives (VI)[4] are not hydrogenated as a result of the hindrance of the catalysis by the substituents R′ and R″ [structure (VII)], while hydrogenation of triptycene derivatives, although small, is in fact possible[3]:



(VI)

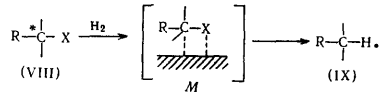


(VII)

The study of the catalytic reactions of homologous compounds with a complex three-dimensional configuration allows the statistical distribution of the active catalyst centres with respect to size to be found in principle[5].

Another approach which makes it possible to estimate not only the geometry of the active catalyst surface but also to take into account the energy interaction between the catalyst and various functional groups in the substrate molecule is the study of the mechanism of the hydrogenolysis of optically active compounds[6]. In this reaction the bond C*–X at the asymmetric carbon atom of the molecule (VIII) is ruptured with formation of the compound (IX); since the reaction involves the asymmetric centre, this

compound can remain either optically active (with retention of inversion of the initial configuration) or lose activity as a result of racemisation:



(VIII) M (IX)

A heterogeneous catalyst, on the surface of which an intermediate state *M* is established, makes its own contribution to the stereochemistry of the complex. On general grounds, it may be expected that the introduction of an interface lowers the symmetry of the system and therefore one would expect retention of the configuration of the reacting molecule. However, experiment shows that reactions often take place with inversion of configuration. The use of optically active compounds in catalysis provides valuable information about the nature of the intermediate state: whether it is symmetrical or asymmetric, and to what extent the non-reacting parts of the molecule are involved in the intermediate complex (for example, by comparing the reactions of a number of homologues). Racemisation at a centre not participating directly in the reaction would indicate that adsorption of the substituents plays a role; in conjunction with isotope exchange, it can provide additional information about the details of the mechanism of the reaction on the catalyst surface.

The number of systematic investigations of the mechanism of catalysis using optically active and sterically complex compounds is so far inadequate and only recently has this field been developed vigorously, particularly by Japanese investigators who have published a series of experimental papers and brief reviews[7], which are of considerable interest from the viewpoint of the stereochemical relations between the configuration of the reacting molecule and the geometry of the catalyst surface. Unfortunately, so far these data are only qualitative but their complete review is nevertheless desirable (up to 1965 inclusive).

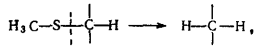
The studies in this field, which were begun by Bonner and coworkers as early as 1952 and then continued by Mitsui, Imaizumi, and others[7], developed on the basis of the hypothesis of the electronic nature of catalytic reactions, the latter being divided into several types depending on whether their mechanisms on the catalyst surface are S_N1, S_N2, or S_Ni. A detailed study has been made of the effect of the structure of the reacting optically active molecule on the type of mechanism and the effect of the nature of the catalyst (mainly Raney nickel and palladium deposited on carriers have been studied).

Extensive experimental data have been accumulated, which in most cases make it possible to establish without ambiguity the mechanism of hydrogenolysis and to draw certain general conclusions concerning the stereospecifity of the action of active catalyst centres.

Hydrogenolysis and hydrogenation of oxygen-containing and other compounds have been widely studied by Mitsui, Imaizumi, and a number of other workers[8,9], who showed that the steric requirements of the reacting molecule have a considerable influence on the rate and mode of reaction.

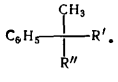
Bonner[10] was the first to use extensively optically active compounds for the investigation of the mechanism of desulphuration. Optically active sulphides, sulphoxides, and sulphones were initially studied as compounds which are firmly chemisorbed on the catalyst surface. The study of the hydrogenolysis of such compounds were also of considerable practical interest for the understanding of the mechanism of the desulphuration of petroleum and many other compounds.

Earlier such studies of the hydrogenolysis of the C–S bond concerned carbohydrates, biotin, and amino-acids, but they were confined to the investigation of hydrogenolysis by a mechanism in which a symmetrical optically inactive product is formed,

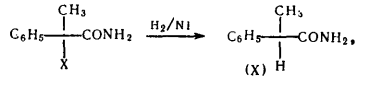


which meant that steric factors were not investigated. However, the reaction proved to be very sensitive to the three-dimensional structure of the substrate. For example, steric hindrance in hydrogenolysis is shown by the greater difficulty of the hydrogenolysis on nickel of phenylthiodiphenylacetic acid compared with the methylthio-compound, etc.[8] Bonner's studies, which were initially undertaken to elucidate the special case of the desulphuration mechanism (hydrogenolysis of the C–S bond), served as a basis for the development of a hypothesis concerning the mechanism of the hydrogenolysis of C–O, C–Cl, and C–N bonds; although formal, this hypothesis fairly correctly reflects the essential features of the processes.

The technique used to study hydrogenolysis is simple. The hydrogenolysis is usually carried out at atmospheric or elevated pressure in boiling ethanol over a period of 1–5 h in the presence of a 2–10-fold excess of catalyst. After the reaction the catalyst is filtered off and the optical activity of the reaction products is studied. Since it is easy to prepare in an optically pure form and has a benzyl group, atrolactic acid, and its derivatives are used as model compounds in most investigations; they have the general formula:



In his initial studies Bonner[10,11] investigated the hydrogeneolysis of the optically active amides of phenylpropionic acid derivatives containing sulphide, sulphinyl, or sulphonyl groups:



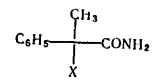
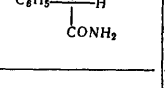
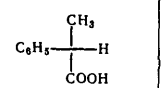
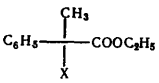
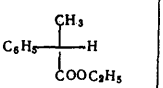
(X)

where X = SC_6H_5, SOC_6H_5, or $SO_2C_6H_5$. These compounds showed the following unusual types of behaviour (see Table 1).

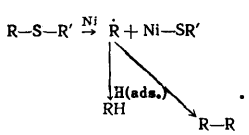
1. The phenylthio-derivative (X = SC_6H_5) gives rise to a completely racemic amide, the loss of optical activity being due to the stereochemical course of the reaction and not secondary racemisation of the amide formed, since under the experimental conditions the optically active compound (X) is racemised only to the extent of 20%.

2. The hydrogenolysis of the optically active sulphoxides (X = SOC_6H_5)[11] also leads to the racemic propionamide (X), which indicates the similarity of the mechanisms of the

TABLE 1. Catalytic hydrogenolysis of sulphur-containing optically active compounds on a Raney nickel catalyst (at 78° in ethanol at atmospheric pressure).

Initial compound			Product					
structure	X	configuration, $[\alpha]_D$	structure	$[\alpha]_D$	optical activity, %	Change in configuration	Type of mechanism	Refs.
	$-SC_6H_5$ $-SOC_6H_5$ $-SO_2C_6H_5$	[(+)C(+)S]; +18.7 [(+)C(−)S]; +55.5 [(−)C(−)S]; −203 [(−)C(+)S]; −53.2 −69.8		0 0 −28.5	0 0 90	rac. » inv.	S_N1 S_N1 S_N2	10,11 11 10,11
				−0.23 −0.35 0	0.24 0.35 0	rac. » »	S_N1 $+S_N2$ То же S_N1	16 16 15
	$-SC_2H_5$ $-SC_4H_9$ $-SC_6H_4CH_3$ $-SO_2C_6H_4CH_3$ $-SO_2C_6H_4CH_3$	$D(+)$ 4.11 $D(+)$ 130.9 $D(-)$ 18.73 $D(-)$ 5.39 $D(-)$ 15.5 $D(-)$ 3.22						
				L-(−) 20.4 L-(−) 51.0 L-(−) 18.8	81 » 75	inv. » »	S_N2 S_N2 S_N2	15 10,11 15
3-Ethylthio-3α,9α-epoxy--11-oxocholanoic acid		+100	3α,9α-epoxy-11-oxocholanoic acid	+88.1		no change	S_N1	18

desulphuration of these compounds to the thoroughly investigated mechanism of the hydrogenolysis of sulphides[12-14], which is of the dissociative free-radical type:

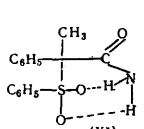


The study of the sulphoxide (X = SOC_6H_5) is complicated by the fact that this compound has two asymmetric atoms (carbon and sulphur) and forms diastereoisomers:

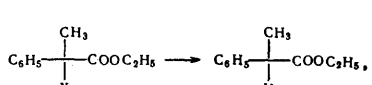
$$[(+)_C(+)_S];\ [(+)_C(-)_S];\ [(-)_C(+)_S];\ [(-)_C(-)_S].$$

However it has been shown[11] that all the stereoisomers give the racemic amide (X) on hydrogenolysis.

3. The hydrogenolysis of the optically active sulphone (X = $SO_2C_6H_5$) proceeds with the retention of up to 90% of the optical activity but with inversion of the configuration. The hypothesis that this behaviour may be accounted for by the structure of the substrate molecule, cyclic structures involving hydrogen bonds with the amide group being formed as in (XI),



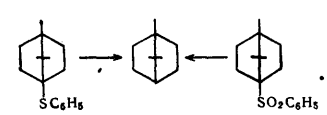
(XI)



(XII)

where X = SC_6H_5, SOC_6H_5, or $SO_2C_6H_5$, is probably incorrect, since the same results (racemisation of the sulphide and reversal of the configuration of the sulphone) are also obtained when the amide group is replaced by an ester group as in compound (XII). In the latter case[16] the degree of racemisation was somewhat greater (25% for *p*-tolylsulphonylpropionate) but the configurational relations remained the same as before. This indicates mainly the specificity of the stereochemical mechanism of the hydrogenolysis and not a peculiarity in the structure of the substrate molecule although in some cases the effect of structure may be significant.

The fact that the hydrogenolysis of ethylthio- and phenylthio-phenylpropionate results in the formation of slightly optically active α-phenylpropionic acid (0.24 and 0.35% of the optical activity[16]) shows that an associative mechanism operates at the same time as the main, dissociative mechanism. A rigid structure, excluding the possibility of the reversal of configuration, favours a process involving the retention of configuration. Thus the desulphuration on nickel of both 4-bornyl phenyl sulphone and phenylthiobornane results in the formation of bornane[17]:

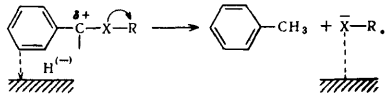


The desulphuration of compounds (XIII) on nickel gives 3α,9α-epoxy-11-oxocholanoic acid (XIV) ($[\alpha]_D$ = 88.1°), also with retention of the configuration by virtue of the rigid structure[18]:

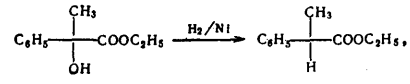


If one bears in mind that the behaviour in the last cases described is determined by the presence of a rigid molecular skeleton and they can scarcely be considered together with the hydrogenolysis of sulphur-containing propionates, the most rational explanation of the very great difference in the behaviour of sulphides and sulphones must be that provided by Bonner's mechanism, according

to which the adsorption of a sulphone molecule on the surface occurs via an oxygen atom, this being followed by the reaction of the hydrogen already adsorbed on the surface with the substrate molecule. The details of this process are as follows. It may be expected that in the hydrogenolysis of benzyl compounds of the type $C_6H_5CH_2-X-R$ adsorption on nickel will result in the transfer of the ring π electrons to the catalyst, as a result of which the α-carbon atom will acquire a certain positive charge which will facilitate attack by a hydride ion formed on the catalyst surface by dissociation of the H_2 molecule into H^+ and H^-. The reaction proceeds with reversal of configuration by an associative mechanism:



Thus if the molecule contains strongly chemisorbed groups which enhance the electron-donor properties of the catalyst, then, as for sulphones, the rupture of the C–S bond does in fact result in inversion of configuration. The validity of this mechanism and the effect of chemisorption have been confirmed by the study of hydrogenolysis of atrolactic acid and its *O*-derivatives. Indeed under the conditions of the hydrogenolysis of sulphides methyl and ethyl L-(+)-atrolacetates gave methyl and ethyl L-(-)-2-phenylpropionate:



with a low degree of racemisation[10,11] (Table 2).

TABLE 2. Hydrogenolysis of optically active derivatives of 2-phenylpropionic acid on nickel and palladium catalysts.

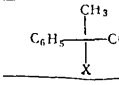
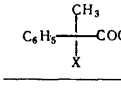
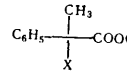
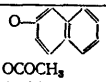
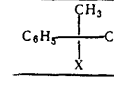
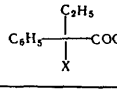
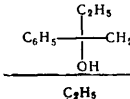
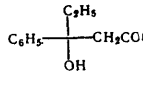
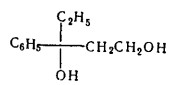
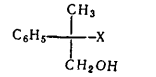
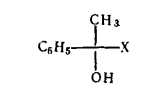
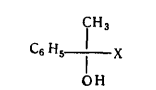
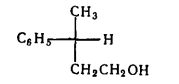
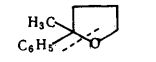
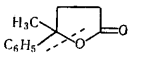
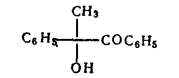
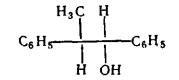
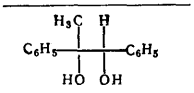
Initial compound: structure	Initial compound: X	Initial compound: configuration, $[\alpha]_D$	Catalyst, time and temperature of reaction	Product: $[\alpha]_D$	Product: optical activity, %	Change in configuration	Type of mechanism	Refs.
1	2	3	4	5	6	7	8	9
	OH	*D* −5.0 *L* +5.0	Ni, 4 h	*D* +86		no change	S_Ni	19
	OH	*D* −20	Ni, 3 h	*D* +45.5	79	no change	»	19
		L +26.1	Ni, 3 h	*L* −35.7	73	ditto	»	19
			Ni, 17 h	*L* −25.0	66	»	»	19
		L +25.3	Ni, 37 h	*L* −73.2		»	»	26
	OCH_3	*D* +46.2	Ni, 2 h	*D* +53.0	72	»	»	30
		D +47.9		*D* +53.7	83	»	»	31
	OC_2H_5	*L* −31.9		*L* −53.4	90	»	»	31
	$OCH_2C_6H_5$	*L* −10.9		*L* −51.9	87	»	»	31
	OC_3H_7		do not react					31
	OC_4H_9							31
	OC_6H_5	*D* +6.2			95	inv.	S_N2	31
		L −2.1		*D* +30.5	95.3	»	»	26
		D +1.2	Ni, 8 h	*L* −6.1	93	»	—	26
		D +6.2	5% Pd/C		47	no change	S_Ni	31
	$OC_6H_4CH_3$-*o*	*D* −7.25	Ni	*L* −31.2	96	inv.	S_N2	24,32
			5% Pd/C		48	no change	S_Ni	24,32
	$OC_6H_4CH_3$-*p*	*L* +3.50	Ni	*D* +23.3	92	inv.	S_N2	24,32
			5% Pd/C		52	no change	S_Ni	24,32
	$OC_6H_4OCH_3$	*L* +13.6	Ni	*D* +34.2	95	inv.	S_N2	24,32
			5% Pd/C		49	»	»	24,32
	$OC_6H_4OCH_3$	*D* −8.4	Ni	*L* −28.2	94	»	»	24,32
			5% Pd/C		64	»	»	24,32
		*D* +4.81	Ni	*L* −29.6	91	»	»	24,32
	$OCOCH_3$	*L* −26.3	Ni	*D* +43.2	67	»	S_N2	33
	$OCOC_2H_5$	*D* +33.3	Ni	*L* −54.9	82	»	S_N2	33
	$OCOC_6H_5$	*L* −33.6	Ni	*D* +23.9	34	»	S_N2+S_N1	33
	NH_2^*	+5.48	Ni, 5 h	+8.57				30
	NHOOCH		do not react					30
	Cl	*L* +2.36	7.7% Pd/C	*L* −7.2	18.1	no change + rac.	S_Ni+S_N1	26
	Cl	*D* −2.01	Ni	0		rac.	S_N1	26
		D −21.3	Pd/C	*D* +9.14		no change	S_Ni	35
		L +20.2	Pd/C	*L* −7.0		ditto	S_Ni	35
	OH	+24.0	Ni, 60°		83	»	S_Ni	29
			Ni, 15°		94	»	»	29
	$OCOC_6H_5$	+28.7	Ni, 15°		10	inv.+ rac.	S_N2+S_N1	29
		+13.3	Ni	−14.5	45	no change	S_Ni	27
		+19.6	Pd/C	+10.7	60	inv.	S_N2	27
		+2.44	Ni	−20.8	100	no change	S_Ni	27
		2.68	Cu	−15.8	69	ditto		27
		2.68	Co	−17.5	76	»		27
		2.44	Pd/C	+14.4	70	inv.	S_N2	27
		2.68	Pd	+13.0	54	»	»	27

TABLE 2 (contd.)

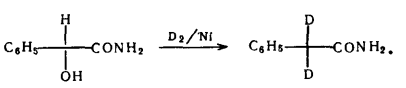
Initial compound: structure	Initial compound: X	Initial compound: configuration, $[\alpha]_D$	Catalyst, time and temperature of reaction	Product: $[\alpha]_D$	Product: optical activity, %	Change in configuration	Type of mechanism	Refs.
1	2	3	4	5	6	7	8	9
		−49.5	Ni	−14.5	98	no change	S_Ni	27
		−46.0	Cu	−13.0	100	ditto	»	27
		−38.7	Co	−10.0	92	»	»	27
		−49.5	Pd/C	12.2	88	inv.	S_N2	27
		−47.6	Pd	8.78	66	»	»	27
	C_2H_5	−5.95	Ni, 0.75 h	9.72		no change	S_Ni	38
	OC_6H_5	−15.0	Ni	8.4	70	inv.	S_N2	46
			Pd	10.0	84	»	»	46
	$OC_6H_4CH_3$-*p*	−48.2	Ni	13.2	92	»	»	46
			5% Pd/C	13.0	90	»	S_N2	46
	$OC_6H_4CH_3$-*o*	+12.1	Ni	−10.9	87	»	»	46
			5% Pd/C	−9.3	74	»	»	46
	$OC_6H_4OCH_3$-*p*	+52.8	Ni	−11.0	87	»	»	46
			5% Pd/C	−10.7	85	»	»	46
	C_2H_5	+17.4	Ni; 1.5 h	+9.72	42	no change	S_Ni	40
					64	ditto	S_Ni	41
	CH_2COOCH_3	+9.43	Ni	−33.5	94	»	»	27
			5% Pd/C	+36.9	100	inv.	S_N2	27
	$CH_2CH_2COOCH_3$	+29.9	Ni	+22.6	96	no change	S_Ni	27
		−30.8	10% Pd/C	+21.2	91	inv.	S_N2	27
	CH_2CH_2COOH	+22.5	5% Pd/C	−16.0	84	»	»	27
		+5.8	Ni	+23.6	100	no change	S_Ni	28,49
			5% Pd/C	+22.1	93.6	ditto	»	28,49
	CH_2CH_2OH	−61.4	Ni	−30.8	74	»	»	27
		−66.5	5% Pd/C	+40.9	91	inv.	S_N2	27
	$CH_2CH_2CH_2OH$	−7.44	Ni	−15.4	95	no change	S_Ni	27
			5% Pd/C	+14.7	91	inv.	S_N2	27
		−5.95	Ni; 0.75 h	+10.94		no change	S_Ni	36
		+3.40	Ni	−12.6	82	ditto	S_Ni	36
			5% Pd/C	+10.7	70	inv.	S_N2	36
		−61.9	1—5% Pd/C	2.35	10	rac.	S_N1	28
			Pd/C	−59.5				47
			$Cu—Cr_2O_3$	+63.5				47
			$Cu—Cr_2O_3$ 200°, 100 atm	11.8				47

* The ring is hydrogenated.

** Foraminate palladium was used.

A product with rotation of the opposite sign was obtained when L-(-)-atrolactate was used as the starting material. Consequently hydrogenolysis occurs with retention of the configuration. Thus the hydrogenolysis of C–SR and C–SOR bonds involves racemisation, the hydrogenolysis of $C–SO_2R$ occurs with retention of the optical activity and reversal of the configuration, while the hydrogenolysis of C–OH bonds occurs with retention of both the optical activity and configuration, which confirms Bonner's mechanism [19]. This mechanism is also confirmed by studies of isotope exchange in the hydrogenolysis of optically active compounds [20].

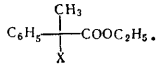
When a deuteriated Raney nickel catalyst in deuterioethanol acts on L-(+)-mandelamide, dideuteriophenylacetamide is formed [21]:



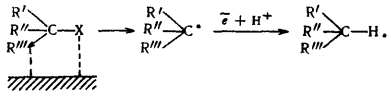
In this process up to 1.7 atoms of deuterium per molecule enter into the benzene ring, which is regarded as proof that the ring is adsorbed on the catalyst surface. Under the same conditions the exchange in (+)-2-phenylpropionamide occurs at the α-C atom and in CH_3 and C_6H_5 groups.

The rate of exchange exceeds initially the rate of racemisation but after 8.5 h the two rates differ only slightly[22]. Identical rates of isotope exchange and racemisation are characteristic of an associative mechanism[23]. These data confirm that, when the substrate contains molecules strongly adsorbed on the catalyst surface and behaving as a catalyst poison (thioethers, sulphoxides), the hydrogenolysis products are fully racemic, but when the molecules contain substituents which do not give rise to appreciable hindrance of the catalytic process and can be adsorbed reversibility, Walden inversion of configuration takes place with almost complete retention of the optical activity, and in some cases the initial configuration is also retained (in atrolactate). These observations led Bonner and then Mitsui, Imaizumi, and others to formulate a hydrogenolysis mechanism based on the hypothesis of nucelophilic substitution at the catalyst surface[24].

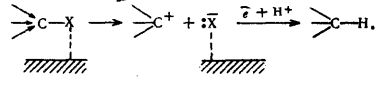
Several reviews exist, mainly in Japanese, but these are very incomplete[7,25] and it is therefore desirable to summarise studies in this field, considering them from the point of view of the study of the nature of the active surface. The following possible reaction mechanisms are examined below, using the hydrogenolysis on nickel of a 2-phenylpropionate or similar compounds as example:



1. Radical splitting is observed for sulphur-containing compounds (X = SC_6H_5, SOC_6H_5); these are powerful poisons of the nickel catalyst on which the SR group is strongly adsorbed; one of the substituents behaves as an electron acceptor, while the adsorption of C_6H_5 and $COOC_2H_5$ groups is much weaker. The C–S bond splits, a proton and an electron adding to the resulting radical and forming a racemic product:



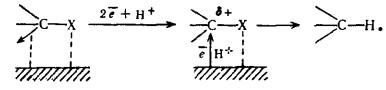
2. An S_N1 mechanism is possible when one or several substituents are weakly chemisorbed and behave as electron donors; The C–X bond (X = SC_6H_5, SOC_6H_5) splits with the formation of a carbonium ion, the addition of hydrogen to which is non-stereospecific and results in the formation of a racemic product:



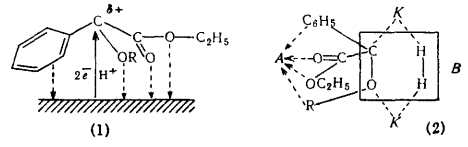
When the carbonium ion is unstable, the addition of $H^+ + 2e$ occurs before the removal of X and the product may contain an admixture of an active compound with inverted initial configuration. Steric hindrance favours the occurrence of the S_N1 mechanism.

3. An S_Ni mechanism is possible when adsorption of X (X = OH, OAlk) is weak and insufficient for the rupture of the C–X bond, and in the absence of appreciable steric hindrance involving the C_6H_5, $COOC_2H_5$, and OR groups. It is assumed that a kind of a cyclic compound is formed from the reacting molecule and the catalyst surface.

The presence of the donor benzyl group results in the attraction of electrons to the catalyst surface which causes the α-carbon atom to acquire a certain positive charge; electrons and protons pass from the catalyst to this atom with the formation of a product with initial configuration:



Mitsui[24], who considered the details of the geometry of the transition state, suggests that the adsorption of all the groups (C_6H_5, $COOC_2H_5$, and OR) occurs on the same area of the catalyst surface [scheme (1)]. In terms of the multiplet theory, this scheme may be represented by formula (2):



In this scheme the centres A and B cannot be identified with the K' centres which are postulated in the multiplet theory to satisfy the principle of micro-reversibility[6].

4. The reaction has an S_N2 mechanism when there is steric hindrance to adsorption of the groups at the asymmetric carbon atom (the hindrance may occur on the catalyst side — when inhomogeneous and geometrically or energetically distinct centres are present on the catalyst surface). For example, in phenoxypropionates (X = OC_6H_5) this group [the CH_3 group? (Ed. of Translation)] cannot be adsorbed alongside the C_6H_5 and $COOC_2H_5$ groups on the same surface, as in the S_Ni mechanism, and they are in fact adsorbed on different areas of the surface, which lowers the steric hindrance to adsorption. Mitsui[24] assumes that, for adsorption of this type to occur, the molecule must be adsorbed on sterically opposite regions of the surface, for example on different sides of the surface of narrow pores.

The multiplet mechanism makes it possible to represent this type of disposition of "extra-indicial"† substituents at the asymmetric carbon atom by assuming the adsorption of the phenyl group in C_6H_5O at the centre A and of the methyl and ethoxycarbonyl groups at a second centre (B). The hydrogenolysis of the C–O bond for this type of disposition of the "extra-indicial" groups results in inversion of configuration (see the mechanism on p. 552).

The suggested mechanism of catalytic hydrogenolysis is based on the study of the hydrogenolysis of a large number of compounds of different structures, mainly derivatives of atrolactic acid and compounds containing the benzyl group with the substituents R′ and R″:

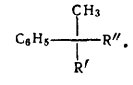


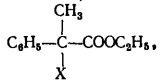
Table 2 lists all the known (up to 1965 inclusive) examples of the hydrogenolysis of such optically active compounds, whose number is steadily increasing. The

† A group of atoms on the catalyst surface which fits the configuration of the reacting group of the adsorbed molecule is known as the "index" in multiplet theory (Ed. of Translation).

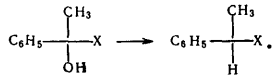
hydrogenolysis of C–O, C–N, C–Cl, and C–C bonds on Raney nickel and palladium catalysts has now been investigated.

Hydrogenolysis of the C–O Bond

The hydrogenolysis of compounds with the general formula



has been studied. The hydrogenolysis of methyl and ethyl atrolactates on nickel occurs stereospecifically by an S_Ni mechanism with retention of the initial configuration[19,26]. The effect on the hydrogenolysis of increasing distance between the $COOC_2H_5$ group and the asymmetric carbon atom has been examined in compounds with X = $= CH_2CH_2COOC_2H_5$ and $CH_2COOC_2H_5$:

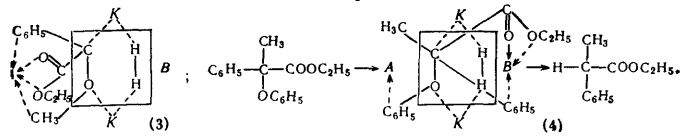


In these compounds, as in the atrolactates[19], the initial configuration is retained, a higher percentage of optical activity being preserved (up to 100% for X = CH_2CH_2. $.COOC_2H_5$[27,28]). However, on palladium/charcoal catalysts these compounds behave differently: the configuration of esters is inverted, while that of the acid (X = $= CH_2CH_2COOH$) is retained, as with the nickel catalyst[28].

If the carboxy group is close to the asymmetric carbon atom, as for example in ethyl 2-hydroxy-2-phenylbutyrate and its benzoyl derivative[29], the hydrogenolysis of the ester on nickel in the presence of added alkali takes place with retention of the configuration and the optical activity (up to 94%), the lowering of reaction temperature favouring greater stereospecificity (S_Ni mechanism). In the benzoyl derivative the optical activity is retained only to the extent of 10%, which is evidence of S_N2 and S_N1 mechanisms, predominantly the latter. This also indicates that the approach of the asymmetric carbon atom to the catalyst surface favours a change to an ionic reaction mechanism involving extensive racemisation of the product.

Alkoxypropionates. The hydrogenolysis of this group of compounds has been studied using nickel and palladium catalysts. On nickel methoxy- and ethoxy-propionates (X = OCH_3 and OC_2H_5) yield 2-phenylpropionate of high optical purity (72–90%) with retention of the initial configuration [multiplet scheme (3)][30,31].

Greater structural complexity of a substituent has differing effects on the reaction. Thus introduction of the benzyloxy-group (X = $OCH_2C_6H_5$) does not influence the stereospecificity of adsorption and the retention of the optical activity (up to 87%), while introduction of propyloxy- or butyloxy-groups (X = OC_3H_7 and OC_4H_9) prevents hydrogenolysis altogether, as a result of high steric hindrance and weak adsorption. An increase in the extent of adsorption of the substituent, for example when a phenoxy- -group (X = OC_6H_5) is introduced, favours hydrogenolysis with retention of optical activity (93–95%) and inversion of configuration (S_N2 mechanism) [multiplet scheme (4)][26]:



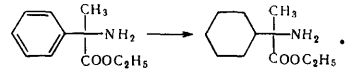
Inversion of configuration with retention of much of the optical activity (88–95%) is also observed for *o*- and *p*-cresyloxy- (X = $OC_6H_4CH_3$), *o*- and *p*-anisyloxy- (X = $= OC_6H_4OCH_3$), and β-naphthyloxy-propionates (X = $= OC_{10}H_7$).[32]

The hydrogeneolysis on 5% palladium/charcoal takes place in a different manner. Phenoxy- and *o*- and *p*-cresyloxy-propionates react by an S_Ni mechanism with retention of configuration (albeit with low specificity – 47, 48, and 52% respectively) which indicates that an S_N2 mechanism makes a certain contribution. However, *o*- and *p*-anisyloxypropionates undergo hydrogenolysis on palladium/charcoal by an S_N2 mechanism with reversal of configuration, the relatively low optical activity (49 and 64%) of the product indicating a greater contribution of the S_N1 mechanism[24,32].

Acyloxypropionates (X = OCOR). Whereas the hydrogenolysis of methoxy- and ethoxy-propionates on nickel occurs with retention of configuration, the hydrogenolysis of aceotoxy- and propionyloxy-propionates on nickel proceeds by an S_N2 mechanism with inversion of configuration and fairly high stereospecificity (67 and 82% of optical activity retained). On the other hand, the benzoyloxy-derivatives also undergo the inversion of configuration (S_N2 mechanism) but in addition there is a marked decrease in the optical activity of the product (optical purity 34%), which suggests the simultaneous occurrence of the S_N1 mechanism as a result of strong adsorption of the benzoyloxy-group[33].

Attempts at Hydrogenolysis of the C–N Bond.

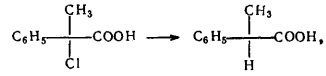
The replacement of the oxygen atom in the atrolactate molecule by nitrogen may result in a change of the mode of reaction. Thus methyl (+)-formamido-2-phenylpropionate is not hydrogenated on Raney nickel, while in ethyl (+)-2- -amino-2-phenylpropionate the benzene ring is hydrogenated with the formation of ethyl (+)-2-amino-2-cyclohexyl-propionate[30]:



Probably the free amino-group facilitates the hydrogenation of the ring[34]. It is striking that this reaction takes place only under hydrogenolysis conditions: on platinum at 4 atm (25°) the ring is not hydrogenated. However, recently[33] it has been shown that at 150° and 60 atm the hydrogenolysis of the C–N bond in 2-amino-2-phenyl-propionic acid occurs on palladium/charcoal with retention of configuration and 70% of the optical activity.

Hydrogenolysis of the C–Cl Bond (X = Cl)

The hydrogenolysis of the C–Cl bond in L-(+)- and D-(-)-2-chloro-2-phenylpropionic acid on 7.7% palladium/charcoal catalyst with formation of L-(-)- and D-(+)-hydratropic acid,

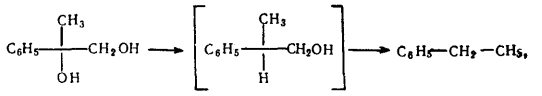


was the first example of hydrogenolysis of an optically active benzyl derivative[35]. The reaction takes place by an S_Ni mechanism with retention of configuration (the

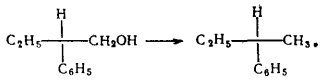
statement in Ref. 35 that the configuration changes is erroneous, see Bonner and coworkers[19]). When the hydrogenolysis is carried out on nickel at a higher temperature, the product is partially or completely racemised, i.e. the reaction takes place to a considerable extent by an S_N1 mechanism[26].

Hydrogenolysis of the C–O and C–C Bonds in Alcohols and Glycols

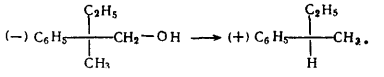
The reduction of the ester group in atrolactates yields a number of corresponding optically active glycols whose hydrogenolysis takes place both at C–O and C–C bonds, for example with formation of ethylbenzene from 2-phenylpropanediol by the following mechanism:



probably via the intermediate formation of phenylpropanol. This pathway is indicated by the hydrogenolysis of 2-phenylbutan-1-ol, for example, which takes place with retention of the configuration of 2-phenylbutane[36]:

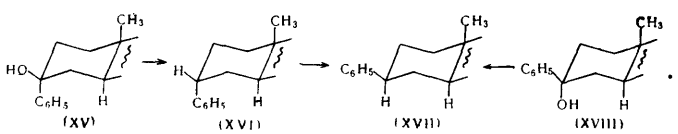


In the hydrogenolysis of phenylpropanediol carbon monoxide is formed from the C_1 atom as a result of the rupture of the C–C bond, which has been demonstrated by the hydrogenolysis of labelled [1-^{14}C]2-phenylpropane-1,2-diol.[37] Reaction by this mechanism should take place largely with retention of configuration, and this has been confirmed by the hydrogenolysis of (-)-2-methyl-2-phenylbutanol on nickel to (+)-2-phenylbutane[21], with retention of 70% of optical activity:



(Bonner[38] erroneously put forward an S_N2 mechanism; actually there is no inversion of configuration and the reaction has an S_Ni mechanism[39].) The hydrogenolysis of (-)-2-phenylbutan-2-ol also occurs with retention of configuration and leads to (-)-2-phenylbutane, 42% of optical activity being preserved[40,41].

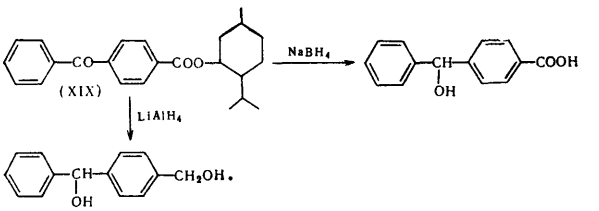
These data show that the presence of two strongly adsorbed groups, phenyl and hydroxyl, favours the retention of the initial configuration in hydrogenolysis on nickel. The structure of that part of the molecule which is not adsorbed has little effect on the reaction mechanism. Thus the hydrogenolysis on nickel of the OH group in 3α-phenylcholestan-3β-ol (XV) proceeds with high stereospecificity and retention of configuration, 3α-phenylcholestane (XVI)[42] being formed, which is then slowly converted into 3β-phenylcholestane (XVII). The latter is readily obtained by the hydrogenolysis of 3β-phenylcholestan-3α-one (XVIII):



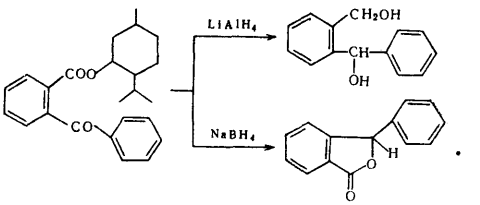
(XV) (XVI) (XVII) (XVIII)

In the hydrogenolysis of 2-phenylethanol the introduction of substituents at the C_2 atom has a significant effect on the proportions of C_1–C_2 and C–O bonds hydrogenolysed, whereas the introduction into the *para*-position of electron-donor or electron-acceptor groups does not affect these proportions[39,43]. The absence of the latter effect indicates only a weak electron interaction and only a weak steric effect of these groups on the stereospecific adsorption of the asymmetric atom participating in the hydrogenolysis.

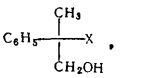
Indeed the steric effect of the asymmetric group is not "transmitted" via the benzene ring when attempts are made to achieve asymmetric synthesis. Thus in the reduction of *p*-benzoylbenzoate by $LiAlH_4$ or $NaBH_4$ inactive products are formed[44]. The action of CH_3MgI on the keto-group in compound (XIX) (asymmetric McKenzie synthesis) also leads to an optically inactive product:



The same result was obtained[45] in the reduction of the corresponding *ortho*-substituted menthyl ester:

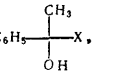


The study of the hydrogenolysis of the hydroxy-ethers of the general formula



where X = OC_6H_5, $OC_6H_4CH_3$, $OC_6H_4OCH_3$-*o*, and $OC_6H_4OCH_3$-*p*, showed that these substances undergo reversal of configuration both on nickel and on 5% palladium/charcoal but retain a high percentage (up to 84–92%) of their optical activity. This finding differs from the results obtained with phenylpropionates of the corresponding structure (replacement of CH_2OH by $COOC_2H_5$) whose initial configuration was retained on hydrogenation on palladium[46].

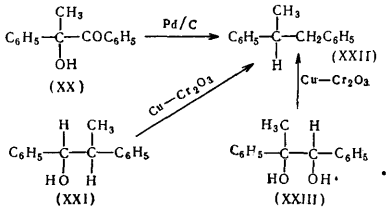
When the distance of the CH_2OH group from the asymmetric centre in the molecule is increased, the configuration is inverted on palladium/charcoal and preserved on nickel. The compound tested had the formula



where X= CH_2CH_2OH and $CH_2CH_2CH_2OH$.

Hydrogenolysis on other catalysts has been little studied. Barnes and Juliano[47] showed that in the hydrogenation of compounds (XX) on palladium/charcoal at a low temperature and of compound (XXI) on a Cu–Cr_2O_3 catalyst at 200°

and 100 atm the optically active 1,2-diphenylpropane (XXII) is formed, with retention of configuration:



However, the formation of L-(+)-(XXII) in the hydrogenolysis of L-(-)-(XXIII) involves extensive racemisation (81.9%).

Comparison of the Stereospecificity of Nickel and Palladium Catalysts in Hydrogenolysis

The study of the hydrogenolysis of optically active compounds permits a more profound understanding of the interaction between the reacting molecule and the catalyst surface. The differences in the mechanisms of hydrogenolysis may be due, on the one hand, to the structure of the reacting molecule, and, on the other hand, to the nature of the catalyst surface. The occurrence of S_Ni and S_N2 mechanisms on various catalysts is interpreted[24] as a result of the adsorption of various groups of the reacting molecules on "different sites" on the catalyst surface or on the opposite sides of the narrow pores in the surface where the adsorption of different sterically hindered groups of the molecule is facilitated, which in fact results in the inversion of configuration. Accordingly, it is to be expected that finely porous catalysts with a larger surface area will tend to give rise to reactions by an S_N2 mechanism, while catalysts with a more homogenous surface, without projecting centres, will give rise to reactions by an S_Ni mechanism.

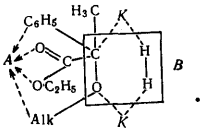
This difference may serve as experimental proof of the presence of projecting centres on the catalyst surface, which are active in relation to the adsorption of particular groups in the molecule; this can serve as an additional technique in the attempts to study the surface of a catalyst by catalytic reactions involving complex molecules which do not undergo inversion of configuration during the reaction[1].

A number of striking features in the behaviour of nickel and palladium has already been noted in the examination of the hydrogenolysis of compounds of different structures. Let us consider these findings in greater detail. Table 2 summarises all the experimental data on hydrogenolysis on nickel and palladium catalysts.

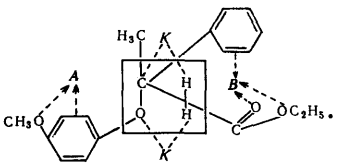
The hydrogenolysis of ethyl 2-phenoxy-2-phenylpropionate (X = OC_6H_5) and also the *o*- and *p*-cresyloxy- and *p*-anisyloxy-derivatives (X = *o*- and *p*-$OC_6H_4CH_3$ and *p*-$OC_6H_4OCH_3$) takes place on nickel by an S_N2 mechanism with inversion of configuration (Table 2). This presupposes the adsorption of aryloxy- and other groups on sterically different surfaces as a result of steric hindrance to adsorption on a single area of the surface. The hydrogenolysis of alkoxy-compounds, for which steric hindrance is less, can also occur on a single area of the surface, which involves no inversion of configuration, the reaction having an S_Ni mechanism. According to Mitsui and Imaizumi[24], "the Raney nickel catalyst has a surface structure such that aryloxypropionates are readily adsorbed on different areas of the surface". ‡ It is suggested that nickel has this type of structure, suitable for the adsorption of molecules whose reaction is sterically hindered because it contains many pores formed as a result of the leaching of the alloy[24]. However, the finding that foraminate palladium in no way differs from metallic palladium is evidence against this[46].

Palladium catalysts on carriers behave differently. Here the effect of the degree of coverage of the carrier surface by the metal on the mechanism of hydrogenolysis is observed. There are no data on the hydrogenolysis of alkoxypropionates and the reaction of phenoxypropionates on 5% palladium/charcoal proceeds, in contrast to the reaction on nickel, with retention of configuration (but it is less stereospecific, 47–52% of the optical activity being retained). When the substrate : catalyst ratio is changed from 1.4 : 0.1 to 1.4 : 15, the percentage of the optical activity retained is almost unaffected (it changes from 30 to 47%). However, the hydrogenolysis of *o*- and *p*-anisyloxypropionates on 5% palladium/charcoal takes place with inversion of configuration[24,26,32] (Table 2).

These data show that the product obtained on nickel retains its initial configuration when fairly strong adsorption of the alkoxy-group in the *A* centre takes place:



Starting with X = OC_6H_5, steric hindrance prevents the location of all three groups at the *A* centre and therefore the phenyl and carboxy-groups are adsorbed at the *B* centre, since OC_6H_5 is held in addition by the "index" centre *K*.



In view of the strong adsorption of oxygen on nickel, such displacement of the phenyl and carboxy-groups from the *A* centre occurs even in the presence of the phenoxy--group whereas on palladium/charcoal this happens only after the introduction of a second oxygen atom — in the anisyloxy-derivative (X = $OC_6H_4OCH_3$).

An increase in the palladium content above 10% alters the type of the mechanism (S_Ni) of the hydrogenolysis of phenoxypropionate[24] and leads to a product with inverted configuration, the reaction having an S_N2 mechanism. Furthermore, Table 3 shows that an increase in the palladium content from 1 to 10% sharply reduces the optical activity of the product (from 65 to 6%), but, starting with

‡ This quotation cannot be found in Ref. 24. Mitsui and Imaizumi[24] use an argument based on the simultaneous adsorption of a sterically hindered molecule on two opposing sides of a catalyst surface; this could occur in suitable pores in the catalyst (Ed. of Translation).

10% Pd, there is a gradual increase in the percentage of optical activity retained in the inverted product, up to 77% for 90% palladium/charcoal (Fig. 1, constructed on the basis of the data in Table 3, shows that the change in the mechanism of hydrogenolysis occurs when the palladium/charcoal catalyst contains 8% Pd). On pure palladium the percentage of the optical activity retained by the product is much lower.

Other Carriers

The deposition of palladium on barium sulphate instead of charcoal (5% Pd/$BaSO_4$) does not change either the reaction mechanism or the stereospecificity, compared with pure palladium (Table 3). However, comparison with the 5% palladium/charcoal catalyst shows that the mechanisms of the reactions on these catalyst are different: S_Ni for palladium/charcoal and S_N2 for palladium/barium sulphate.

According to Mitsui[24], the reason for this behaviour is that at a low palladium concentration the catalytic surface on which phenoxypropionate can be adsorbed is relatively small, since palladium is spread in a thin layer. As the thickness of the layer increases, which is achieved by increasing the concentration of palladium or reducing the surface area of the carrier (the use of barium sulphate),

TABLE 3. Effect of additives and the concentration of the catalyst on carriers on the mechanism of hydrogenolysis.

Initial compound: structure	Initial compound: configuration, $[\alpha]_D$	Initial compound: catalyst (% of metal on carrier)	Product: $[\alpha]_D$	Product: optical activity, %	Change in configuration	Type of mechanism	References
$C_6H_5CH(CH_3)COOC_2H_5$ (OC$_6$H$_5$)	*L*-(+)6.2	Pd/C 1%	*L* −20.3	65	no change	S_Ni	24
		10%	*D* +2.0	6	inv.	S_N2	24
		25%	*D* +5.9	18	»	»	24
		50%	*D* +9.5	30	»	»	24
		75%	*D* +15.6	49	»	»	24
		90%	*D* +24.8	77	»	»	24
		Pd	*D* +13.9	44	»	»	24
		Pd/$BaSO_4$ 5%	*D* +14.2	44	»	»	24
	D-(−)	Pd/Al_2O_3 0.2%	*D* +11.2	31	no change	S_Ni	24
		0.5%	*D* +5.2	15	ditto	»	24
		1%	*D* +1.1	3	»	»	24
		2%	*L* −5.9	16	inv.	S_N2	24
		5%	*L* −25.4	71	»	»	34
		10%	*L* −27.1	76	»	»	24
	D (−)9.5	Ni, 1 h	−28.4	70	»	S_N2	48
		Ni+0.5 g NaOH	−37.7	93	»	»	48
		0.5 g NaCl	−29.8	74	»	»	48
		0.5 g KBr	−33.9	84	»	»	48
	D (−)9.5	5% Pd/C	+13.3	33	no change	S_Ni	48
		Pd/C+0.001 mole NaOH	−34.1	85	inv.	S_N2	48
		Pd/C+0.001 mole HCl	−8.1	20	»	S_N2	48
		Pd/C+0.001 mole KBr	−26.4	65	»	S_N2	48
		Pd/C+0.001 mole NaCl	+11.2	28	no change	S_Ni	48
	L-(+)6.2	Ni/Kieselguhr	*D* +31.1	97	inv.	S_N2	24
		Ni(Urushibara catalyst)	*D* +32.1	100	»	»	24
$C_6H_5CH(CH_3)COOC_2H_5$ (O-C$_6$H$_4$-OCH$_3$)	*L*(+)10.9	Pd/Al_2O_3 0.2%	*D* +29.5	81	»	S_N2	24
		1%	*D* +28.1	77	»	»	24
		5%	*D* +27.6	76	»	»	24
		Pd/C 1%	*D* +19.3	53	»	»	24
		5%	*D* +23.3	64	»	»	24
		50%	*D* +27.8	77	»	»	24
$C_6H_5CH(CH_3)CH_2CH_2COOH$ (OH)	+5.8	Pd/C 1%	+23.6	100	no change	S_Ni	49
		5%	+23.2	98.3	ditto	»	44

TABLE 3 (contd).

Initial compound: structure	Initial compound: configuration, $[\alpha]_D$	Initial compound: catalyst (% of metal on carrier)	Product: $[\alpha]_D$	Product: optical activity, %	Change in configuration	Type of mechanism	References
$C_6H_5CH(CH_3)CH_2CH_2COOH$ (OH)	−4.4	Pd/C 10%	−17.1	93.4	no change	S_Ni	49
		25%	−17.9	97.5	ditto	»	49
		50%	−17.7	96.6	»	»	49
		75%	−18.2	99.2	»	»	49
		Pd/C+HCl 5%	−16.7	91.1	»	»	49
$C_6H_5CH(CH_3)CH_2CH_2COOCH_3$ (OCOC$_6$H$_5$)	+1.88	Pd/C—(A) 1%	−20.9	84.5	»	S_Ni	49
		10%	−15.2	61.3	»	»	49
		50%	−8.2	33.2	»	S_Ni	49
	+1.38	Pd/C—(B) 1%	−9.9	54.6	»	S_N2	49
		10%	−8.8	48.1	»	»	49
		Pd/C—(A) 1%	−12.5	68.6	»	»	49
		NaOH 10%	−8.7	47.4	»	»	49
$C_6H_5CH(CH_3)C_2H_5$ (OH)	−14.9	Pd/C—(A) 1%	+15.7	84.5	inv.	S_N2	50
	+13.7	5%	−16.8	90	»	»	50
		20%	−19.5	95	»	»	50
	−14.9	Pd/C—(B) 10%	+18.7	91	»	»	50
	(+)33	Pd	−7.7	91	»	»	50
	(−)89	Pd/C 5%	+20.2	90.5	»	»	50
	56%	Pd/C—B 5%	−11.9	88	»	»	50
		Pd/C 10%	−14.1	95	»	»	50
	12.7%	Pd/R	−3.7	100	»	»	50
	56%	PtO_2 (+HCl)	−1.65	72	»	»	50
	+13.7°	Ni—R	+19.6	97	no change	S_Ni	
	−13.0°		−10.7	77	ditto	»	50
	12.7%		+13.6	65	»	»	50
	12.7%	Co—R	1.85	24	»	»	50
	(+)48	Pd/Ni	+12.0	5.5	»	»	50
	(+)48	Pt—Ni	11.7	6.5	»	»	50
	(−)65	Cu—Cr_2O_3	−18.3		»	»	50
	+48	Cu—R	+11.3	8	»	»	50
	−48	Co—R	−1.5	55.5	»	»	50
	−48	Pt/C	−8.1	80	»	»	50
$C_6H_5CH(CH_3)C_2H_5$ (OCO-C$_6$H$_4$-COOH)	+34.4	Pd/C—(A) 1%	+13.6	85	inv.	S_N2	50
	−33.5	5%	−15.5	91	»	»	50
	+34.4	10%	+14.1	86.5	»	»	50
	−33.5	20%	−18.0	90	»	»	50
	+34.4	Pd/C—(B) 1%	+14.2	87	»	»	50
	−33.5	5%	−17.7	97	»	»	50
	+34.4	10%	+14.9	88.5	»	»	50
	−33.5	Ni	−13.3	85.5	»	»	50
	(+); 73%	Pt—C 5%	+18.0	94	»	»	50
	(+); 73%	Pd	+19.8	98	»	»	50

Note. The letter R denotes Raney catalysts.

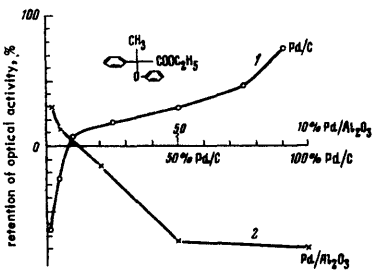


Fig. 1.

the microroughness of the surface becomes more pronounced and a substrate molecule can be adsorbed at two points on the surface, which leads to an inverted product. The stereospecificity of the reaction increases with the number of such centres, reaching a maximum (77% for Pd/C = = 9 : 1) and then falling sharply (44% for pure palladium).

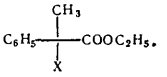
The explanation of this behaviour of pure palladium is[24] its lower dispersion and the absence of pores of suitable

dimensions. The behaviour of palladium/barium sulphate, whose specific surface and porosity are low, is also similar.

The replacement of charcoal by alumina leads to similar results, but here a change in the mechanism of hydrogenolysis is observed for 1.2 Pd/Al_2O_3 (Fig. 1, curve *2*). For this reason, the formation of structures favouring three-point adsorption on sterically different centres, which leads to inversion of configuration, begins on Pd/Al_2O_3 catalysts with a much lower palladium content. This type of behaviour of the Pd/Al_2O_3 catalysts may be due to the smaller specific surface of alumina compared with charcoal[24]. The change in mechanism on the palladium/charcoal and palladium/alumina catalysts is observed at the same degree of coverage of the carrier surface: about 3% of the monolayer. Hence it follows that for palladium dispersed into atoms on the surface the Pd–Pd distances between the centres are 13–15 Å, which corresponds to the dimensions of the phenyl(phenoxy)propionate molecule (Fig. 2). When the distances between the centres are reduced, conditions favouring an S_N2 mechanism are created. Regardless of the method of preparation, the nickel catalysts (Raney nickel, nickel on Kieselguhr, Urushibara nickel) probably have a surface structure such that the distances between the active centres do not exceed about 10 Å. On such centres the hydrogenolysis of phenoxypropionate takes place with inversion of configuration (Table 3).

The study of the effect of additives (NaOH, HCl, KBr) to the catalysts (nickel and palladium/charcoal) showed that, in the presence of alkali or potassium bromide (and to a lesser extent sodium chloride), the degree of inversion increases on both catalysts — on nickel catalysts there is an increase in the degree of inversion and on palladium catalysts a decrease in the percentage retention of the initial configuration: the contribution of the S_N2 mechanism increases. Addition of HCl to palladium/charcoal also increases the contribution of the S_N2 mechanism, but to a lesser degree than the addition of alkali and potassium bromide (Table 3)[48].

For other groups of the molecule, with different adsorption capacity and steric relations, a different type of variation with the catalyst concentration on the carrier and with the additive may be observed. Thus the hydrogenolysis of the sterically more complex molecule, ethyl 2-(*p*-anisyloxy)-2-phenylpropionate (X = $OC_6H_4OCH_3$),



on both nickel and palladium/charcoal and palladium/alumina catalysts involves the reversal of configuration over a wide range of palladium concentrations. The high degree of retention of the optical activity by the product also shows that here the structure of the substrate molecule determines the sterospecificity of the process. When the palladium content is increased from 0.2 to 50% on charcoal and alumina, there is little change in stereospecificity (53–81%)[24].

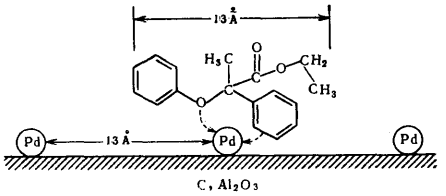
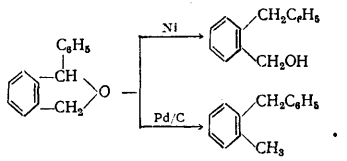


Fig. 2.

Hence it is evident that the difference between the nickel and palladium catalysts is also due to their different capacity to adsorb polar groups. In the case of phenoxypropionate steric factors predominate and the degree of coverage of the carrier surface by palladium greatly influences the reaction mechanism. In the hydrogenolysis of compounds with strongly adsorbed groups, for example the anisyloxy-group, the affinity of palladium for polar groups is the decisive factor; they become strongly adsorbed and the reaction proceeds with inversion of configuration, regardless of the palladium concentration on the carrier.

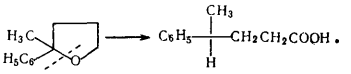
The much lower degree of adsorption on 7.7% palladium/charcoal compared with the nickel catalyst may be the reason for the partial retention (up to 18%) of the initial configuration (S_N2 + S_Ni mechanisms) in the hydrogenolysis of ethyl 2-chloro-2-phenylpropionate (Table 2)[26,35]. For example, the lower affinity of palladium, compared with nickel, for oxygen-containing groups explains also the different pathways of the hydrogenolysis of phenylphthalenes[48]; hydrogenolysis on nickel leads to *o*-benzoylbenzyl alcohol while on palladium/charcoal *o*-benzyltoluene is formed:



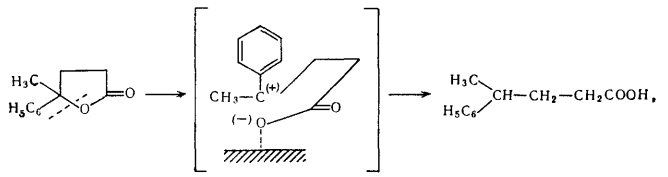
The presence in the reacting molecules of groups which can be strongly adsorbed has a significant effect on the reaction mechanism and it is interesting to compare the hydrogenolysis on nickel and palladium of a number of glycols and hydroxy-acids and their oxygen-containing derivatives. Thus the hydrogenolysis of atrolactic acid derivatives on nickel takes place mainly with the inversion of configuration, and the replacement of $COOC_2H_5$ by CH_2OH in these molecules does not alter the hydrogenolysis mechanism. However, the removal of the methoxycarbonyl group to a position more distant from the asymmetric centre by one or two CH_2 groups alters the mechanism to S_Ni on nickel, cobalt, and copper, probably because, as a result of an increase in the mobility of the alkyl chain, the molecule can be adsorbed without inversion of configuration on "one side" of the catalyst surface by way of "W-shaped" adsorption. In hydrogenolysis on palladium/charcoal catalysts the replacement of $COOC_2H_5$ by CH_2OH changes the S_Ni mechanism to the S_N2 mechanism, probably as a result of only weak chemisorption of the molecule on the surface. Here the removal of the $COOCH_3$ group further away from the asymmetric centre favours hydrogenolysis by an S_N2 mechanism[27]. However, if chemisorption is enhanced, for example by the replacement of methyl γ-hydroxy-γ-phenylvalerate (Table 2) by the free acid, then the reaction on both palladium and nickel proceeds by an S_Ni mechanism[28] and a change in the concentration of palladium does not alter the reaction mechanism and has little effect on the retention of optical activity (Table 3)[49]. The addition of HCl to the 5% palladium/charcoal catalyst is also without effect.

As pointed out above (see Table 2), benzoylated hydroxy-acids impede adsorption on nickel and change the mechanism from S_N2 to S_N1[33]. There are no such data for hydrogenation on palladium. However, it is known that the hydrogenolysis of methyl γ-hydroxy-γ-phenylvalerate and butyrate involves the inversion of configuration[27] (Table 2), while the hydrogenolysis of the free acids proceeds by an S_Ni mechanism. In the hydrogenolysis of a benzoylated acid on palladium/charcoal catalyst in the presence of alkali a decrease in the degree of retention of the optical activity with increase in palladium content in the catalyst is observed, which indicates a gradual increase of the contribution of the S_N2 mechanism[49] (Table 3).

Different mechanisms are also observed in the hydrogenolysis of 2-methyl-2-phenyltetrahydrofuran (S_Ni on nickel and S_N2 on palladium/charcoal[27]).



However, when a second oxygen atom is present in the ring, for example in the hydrogenolysis of γ-phenylvalerolactone on palladium/charcoal,



the reaction proceeds by an S_N1 mechanism with extensive racemisation (10% of optical activity is retained)[28] (Table 2). The difference in the action of the catalysts can probably be accounted for by the lower affinity of palladium for electronegative elements[27].

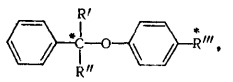
The stereospecificities of the nickel and palladium catalysts may be compared and the effect of the palladium concentration may be assessed by studying the hydrogenolysis of compounds capable of being adsorbed without much steric hindrance for any orientation on the catalyst surface. 2-Phenylbutan-2-ol was chosen as a model compound of this kind[50]. Tables 2 and 3 show that the hydrogenolysis of this alcohol and its methyl ether on foraminate (Raney) nickel, cobalt and copper catalysts and also nickel promoted with palladium and platinum proceeds with formation of 2-phenylbutane, retention of configuration, and high (up to 97%) stereospecificity[50]. It should be noted that in other studies[40,41] such high percentage retention of optical activity was not observed.

Palladium catalysts of different origins and with different palladium concentrations on charcoal as well as catalysts containing added acid (Pd/C–A) or base (Pd/C–B) also showed high stereospecificity, but the hydrogenolysis of 2-phenylbutan-2-ol and its methyl ether occurs with inversion of configuration (S_N2). Furthermore, whereas the hydrogenolysis of 2-phenylbutan-2-ol on the palladium/charcoal catalyst in alcohol occurs with inversion of configuration, in benzene the initial configuration is retained[50]. This demonstrates the different stereospecificities of the nickel and palladium/charcoal catalysts, which form intermediate complexes of different geometry because of the differences in the bond energies of the hydroxyl and the catalyst surface. The latter is significantly influenced by the solvent. In contrast to palladium/charcoal, the rate of hydrogenolysis on nickel is higher in polar oxygen-containing solvents.

However when significant steric hindrance prevents adsorption, as for example in the hydrogenolysis of 1-methyl-1-phenylpropyl hydrogen phthalate, then on Raney nickel promoted with platinum and palladium and also on palladium/charcoal, platinum/charcoal, and metallic palladium hydrogenolysis proceeds only by an S_N2 mechanism with inversion of configuration (Table 3)[50]. Thus the nature of the catalyst and the concentration of palladium on the carrier do not play any role in this case. Hydrogen adds, as it were, from "behind" the substituents adsorbed on the surface and hydrogenolysis proceeds with inversion of configuration.

Thus the study of the mechanism of the hydrogenolysis[51] of optically active compounds opens up new possibilities for the investigation of the active surface of catalysts and it is extremely interesting to investigate, apart from palladium/charcoal and palladium/alumina catalysts, also catalysts on other carriers with specific surfaces of the order of 10–100 $m^2\ g^{-1}$ in order to establish the lower limit of the concentration of palladium at which the mechanism of hydrogenolysis changes.

An increase in stereospecificity can probably also be obtained on dilute catalysts using specific carriers which adsorb selectively the optically active groups of the substrate molecule. This can be shown, for example, in the hydrogenolysis of diastereoisomers of the type:



(where $\overset{*}{R}'''$ contains the asymmetric centre) on a catalyst deposited on a carrier (natural or synthetic polymer, silica gel formed by a specific procedure[52–54], etc.) capable of asymmetric adsorption[55]. According to Kubitscheck and Bonner[44], in such a compound the asymmetric centres $\overset{*}{C}$ and $\overset{*}{R}'''$ do not interact sterically and consequently the reaction of the asymmetric carbon atom $\overset{*}{C}$ can serve as a kind of indicator of the stereospecificity of the process and $\overset{*}{R}'''$ determines the asymmetric adsorption.

Thus a change in the reaction mechanism can serve as an indicator of the stereospecificity of chemisorption during catalysis, which is sensitive both to steric and energy factors in the interaction between the groups of the substrate molecule and the catalyst surface. Thus for palladium/charcoal there is a limiting surface coverage equal to 3% of a monolayer, which results in a change of the mechanism (from S_Ni to S_N2) in the hydrogenolysis of phenyl phenoxypropionate.

Both pronounced sorption and strong steric interactions are observed on nickel. The adsorption is strong in the hydrogenolysis of chloropropionate (X = Cl, S_N1 mechanism). The adsorption is weaker in the hydrogenolysis of propionates with X = OH, OCH_3, C_2H_5, and $OCH_2C_6H_5$, alcohols, and glycols, and compounds with a long chain between the two adsorption points (S_Ni mechanism). Adsorption and steric hindrance occur in the hydrogenolysis of propionates when $X = OC_6H_4{-}OCOC_2H_5$, and of ethylene glycol monoethers (S_N2). Pronounced steric hindrance ($X = OCOC_6H_5$) leads to a mixed mechanism ($S_N2 + S_N1$).

Since strong adsorption and marked steric hindrance lead to a non-specific S_N1 mechanism, it is evident that the nickel surface exhibits considerable inhomogeneity, of both the geometrical and the energy type, i.e. a considerable degree of "microroughness", since an S_N1 mechanism

presupposes that the asymmetric carbon atom is distant from the catalyst surface.

Weak steric and adsorption interaction has been observed on the palladium/charcoal catalyst: (1) the weak adsorption of propionates with X = Cl, OC_6H_5, and $OC_6H_4CH_3$ leads to an S_Ni mechanism; (2) weak adsorption also gives rise to steric hindrance for the propionates with R = OC_6H_5 and OCH_3, alcohols, glycols, and compounds with long chains between the two points of weak adsorption (methyl esters of hydroxy-acids): an S_N2 mechanism obtains. However, enhanced adsorption (hydroxyvaleric acid) changes the mechanism to S_Ni (as on nickel).

Hence it may be concluded that the surface of the palladium/charcoal catalyst is geometrically and energetically more homogeneous than that of nickel and that polar groups are not strongly adsorbed on it. The reaction is always stereospecific: the asymmetric carbon atom is close to the surface and the reaction mechanism is largely S_Ni or S_N2. The steric hindrance associated with the "extraindicial" substituents in the multiplet reaction "index" can play a considerable role. Thus phenylpropionates with X = OC_3H_7 and OC_4H_9 do not react at all, while those with X = OC_2H_5 and $OCH_2C_6H_5$ undergo hydrogenolysis with retention of the original configuration. The bond energies Q_{OK} in the hydrogenolysis "index" must be corrected for the steric interaction between the OR radicals, in conformity with the principle of the energy correspondence of the multiplet theory of catalysis[56].

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