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Potassium Hydride, a Highly Active New Hydride Reagent. Reactivity, Applications, and Techniques in Organic and Organometallic Reactions[1-3]

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Potassium hydride is extremely reactive both as a base and as a hydriding agent. In both of these reactions it is far more reactive than either sodium hydride or lithium hydride. Potassium hydride surpasses finely divided potassium metal as a base yet possesses none of the latter's electron-transfer properties (reduction, coupling, etc.). KH reacts rapidly at 20–25° with excess triethylmethanol to yield the alkoxide quantitatively in <1 min, in contrast to K (80% complete in 20 min with very slow further reaction), NaH (5% in 20 min), and LiH (0% in 20 min). KH also rapidly metalates unhindered amines (*e.g.*, pyrrolidine) and dimethyl sulfoxide. In tetrahydrofuran suspension, metalation similarly proceeds rapidly with highly hindered weak acids such as bis(trimethylsilyl)amine ($pK_A = 28–29$), *N*-isopropylaniline ($pK_A = 26$), triethylmethanol ($pK_A = 22$), and 2,6-di-*tert*-butylphenol ($pK_A = 17–18$). Under comparable conditions, only the latter reacted significantly with NaH; none react with LiH. Ketones are metalated to potassium enolates in high to quantitative yield; no reduction of carbonyl groups by hydride is observed. KH reacts rapidly with weak and hindered Lewis acids under conditions where NaH is very sluggish and LiH is essentially inert. Hindered trialkylboranes are readily converted to the corresponding borohydrides ($K^+ \ {}^-HBR_3$) at room temperature; the very weakly acidic triisopropyl borate reacts similarly. Reactions with KH appear to be entirely heterogeneous, occurring at the crystal surface. Potassium hydride is thermally stable and readily handled as a dispersion in mineral oil. In the absence of the protective oil, it must be protected from air and moisture. Detailed handling procedures are discussed.

Saline hydrides are potentially attractive as strong bases, metalating agents, and hydride sources:[4a] they are insoluble in nonreactive organic solvents[5] and readily separated from products; the acid–base reaction is essentially irreversible; the sole by-product of metalation is an inert insoluble gas (H_2) and there is none at all from hydride transfer; the equivalent weights are lower than those of the analogous amides, alkoxides, etc.; the hydrides are prepared directly from the elements[6] and are indefinitely stable; and the three lower members of the series are commerically available. The chief drawback arises from the insolubility: reactions apparently proceed at the crystal surface with the usual problems of such reactions (surface area effects, poisoning, etc.).

Of the saline hydrides, only NaH has found extensive use in synthesis.[7-10] In general, NaH has been successful only in reactions involving relatively acidic compounds (*e.g.*, ethyl acetoacetate, unhindered alcohols); metalation of rather less acidic compounds (*e.g.*, cyclohexanone, indene) requires prolonged heating.

Examination of the physical and thermochemical properties of the group I hydrides suggests that reactivity should increase proceeding down the group to CsH. The crystal lattice energies[4b,11] decrease considerably from LiH to CsH, and the "apparent" hydride ion radius[4c] in the crystal increases from LiH to KH and then is nearly constant (Figure 1). As reactions of the hydrides apparently proceed at the crystal surface, the lower lattice energy would be expected to be reflected in a greater facility of reaction, which involves removal of M^+ and H^- from the crystal. The larger hydride radius could reflect lower covalency or less compression of H^-; either would be expected to increase reactivity. KH appeared to present the optimum balance of potential reactivity and practical considerations (availability, cost, etc.). In fact, KH has proven remarkably reactive, markedly more so than NaH.

Results and Discussion

Reactivity. Reactivity of the hydrides and of potassium metal was initially compared in reactions with an excess of pyrrolidine, dimethyl sulfoxide, and triethylmethanol. Pyrrolidine is completely metalated in 2–3 hr at room temperature by KH, while no reaction is observed with either a potassium dispersion or NaH. At elevated temperatures (≥75°), both K and NaH react slowly liberating hydrogen; however, at 75° the amide evidently undergoes secondary decompositions as fast as formed for the solutions never develop sufficient base strength to deprotonate triphenylmethane indicator detectably. KH reacts rapidly (8 min) with dimethyl sulfoxide at 25°, whereas NaH requires a temperature of 70–75° for reaction.[12,13] Triethylmethanol reacts completely with KH in less than 1 min at 25°, while NaH reacts only slightly in 0.5 hr. With K, the reaction is moderately rapid initially but becomes very sluggish after 60–75% reaction. In all three cases, LiH failed to react under comparable conditions at 25° (Figure 2).

Solvents. The solvents which appear most suitable for reactions of KH are ethers, especially tetrahydrofuran (THF) and the glyme solvents. Aliphatic and aromatic hydrocarbons are inert to KH—no metalation of alkylbenzenes such as toluene occurs even at 100°—but many reactions are more sluggish in these solvents, possibly due to coating of the KH surface by the insoluble products. Ketones, esters, and nitriles with α hydrogens react rapidly with condensation. Primary and secondary amides, anilines, and alcohols are rapidly metalated. Dimethylformamide appears to be reduced, yielding dimethylamine upon hydrolysis; this is so far the only observed reduction of a carbonyl group at 25° by KH. Dimethyl sulfoxide is rapidly metalated. Hexamethylphosphoric triamide and tetramethylurea appear stable at room temperature, but some loss of KH activity occurs in suspensions maintained at elevated temperatures (≥75°). Prolonged stirring of KH with nonreacting solvents (*e.g.*, THF), followed by decantation, reveals no detectable dissolved hydride.

Many of the potassium salts produced by metalation with KH are moderately to highly soluble in THF, as are the complex borohydrides from hydriding of alkyl and alkoxyboranes; in cases of low solubility, addition of 1–2 equiv of triglyme may markedly improve solubility, presumably by increased solvation of K^+. Potassium alkoxides and potassium trialkylborohydrides are generally soluble in hydrocarbons.

Tetrahydrofuran appears to be the medium of preference for metalation and hydriding reactions and has been generally employed in the reactions discussed below.

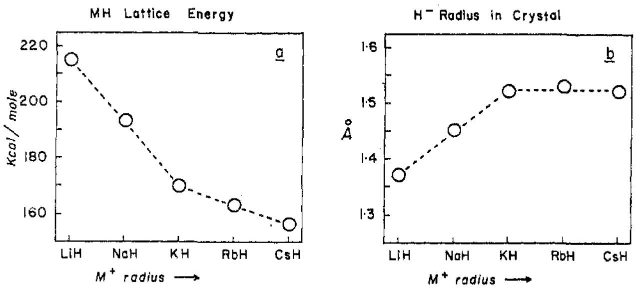


Figure 1. Group I saline hydrides: (a) crystal lattice energy (*cf.* ref 4b and 11); (b) effective hydride ion radii in crystal from lattice constants and Goldschmidt radii of metal ions (*cf.* ref 4c).

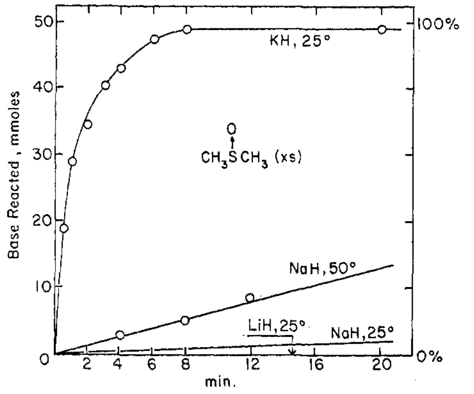


Figure 2. Reaction of group I saline hydrides with excess dimethyl sulfoxide (DMSO) as solvent to yield methylsulfinylmethide ("dimsyl") ion. Comparable figures of reactivity of the hydrides and potassium metal with amines and alcohols have been published (*cf.* ref 3b).

Metalation of O–H and N–H. A wide variety of weakly acidic O–H and N–H-containing compounds react rapidly with KH in THF suspension to yield the corresponding potassium salts quantitatively. Among these are carboxylic acids, phenols, alcohols, primary and secondary amides, and anilines. Aliphatic amines are generally unreactive in THF, but ethylenediamine in excess (2:1 EDA-KH) is metalated in 1–2 hr to yield a suspension of the alkamide; the alkamide suspension is relatively unstable, losing base activity (by titration using triphenylmethane as an indicator[14]) through attack on solvent.

Of particular interest is the facile preparation of such synthetically useful hindered bases as bis(trimethylsilyl)amide (I),[15] *N*-isopropylanilide, trialkylmethoxide (II),[16] and 2,6-di-*tert*-butylphenoxide (III).[17] In these cases reaction with potassium metal is sluggish or nonexistent, and—as expected—NaH and LiH are generally unreactive. The procedure is simple and direct: addition of the conjugate acid to a suspension of KH in THF; controlled addition is necessary in most cases to prevent excessively vigorous hydrogen evolution. Metalations are generally carried out with a slight excess of hydride which may be removed by filtration or decantation (the phenoxide is slightly soluble in the absence of polyether cosolvents); use of an excess of the acid or stoichiometric quantities is also satisfactory, although for obvious reasons longer reactions times result. Glyme solvents are equally satisfactory; benzene or cyclohexane function well only in the case of alkoxides. Reaction times with 1.25 equiv of KH vary from 1 min (2,6-di-*tert*-butylphenol) to 30 min (bis(trimethylsilyl)amine). Metalations of these sterically hindered compounds have been tabulated in ref 3e.

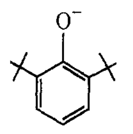
$(CH_3)_3Si\bar{N}Si(CH_3)_3$

I

R_3CO^-

II

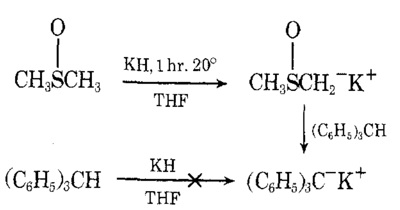
$R = C_2H_5, C_6H_{11}$, *etc.*



III

Metalation of C–H. Potassium hydride in THF rapidly metalates a variety of weak carbon acids such as cyclopentadiene ($pK_A{}^{18} = 15$), fluorene ($pK_A{}^{18} = 23$–25), and dimethyl sulfoxide (DMSO) ($pK_A{}^{18} = 31$–35); in contrast, NaH reacts readily only with the most acidic compounds (*e.g.*, cyclopentadiene). Triphenylmethane is not directly metalated by KH in THF at an appreciable rate but may be metalated through *in situ* formation of "dimsyl" potassium ($CH_3SOCH_2{}^-K^+$); the use of catalytic quantities of DMSO appears feasible but has not been generally explored (Scheme I).

Scheme I



$$CH_3\overset{O}{\overset{\|}{S}}CH_3 \xrightarrow[THF]{KH,\,1\,hr,\,20^\circ} CH_3\overset{O}{\overset{\|}{S}}CH_2{}^-K^+ \xrightarrow{(C_6H_5)_3CH}$$

$$(C_6H_5)_3CH \xrightarrow[THF]{KH} \!\!\!\!\!\!\times\;\; (C_6H_5)_3C^-K^+$$

Ketones ($pK_A{}^{19} \approx 21$)—as well as the more acidic β-dicarbonyl compounds—react very readily with KH in THF to yield the potassium enolates, in most cases quantitatively. Hindered ketones such as 2,4-dimethyl-3-pentanone, 2,6-dimethylcyclohexanone, and isobutyrophenone are completely metalated in 10–15 min at room temperature.

Reaction of ketones with LiH and NaH has been observed to be very sluggish. Relative reactivity of the hydrides has been compared for metalation of pinacolone in THF at 20°, pinacolone presenting a readily available structure relatively open to reaction with base yet hindered toward aldol condensation and reduction. The contrast between the various metal hydrides is striking; complete 20% and 5% reaction, respectively, in 2 hr.[20a]

To confirm that these results were not artifacts of particle size differences, a particularly finely divided dispersion of NaH was obtained.[21] Examination with a calibrated field microscope showed a range of particle sizes, with the most prevalent being a needle of ~3-μm diameter; KH appears as cubes with the most common size being 6–8 μm in diameter. Sedimentation in pentane (NaH has only a slightly lower density than KH) was much slower with this NaH sample than with KH, indicating a considerably higher proportion of fines. Despite the apparently greater degree of dispersion of this NaH sample, it was *still* markedly less reactive than KH toward pinacolone, 60% reaction in 2 hr (*vs.* 100% in 5 min for KH). We believe this confirms that greater reactivity is inherent in KH.

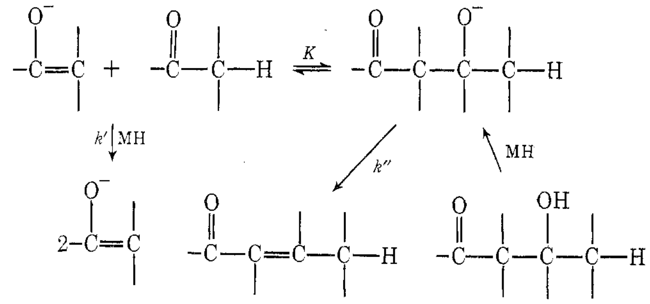
Many ketones—especially unhindered cyclic or methyl ketones—suffer substantial aldol condensation in competition with metalation by lighter saline hydrides.[20b] However, with KH condensable ketones such as 2-heptanone, cyclohexanone, acetone, and even cyclopentanone are metalated in 80–100% yield. The lack of competing aldol condensation may reflect the speed of KH metalation, removing ketone from the aldol equilibrium (Scheme II) faster than irreversible enone formation occurs. Moreover, the aldol equilibrium appears to be favored by tightly associating cations[22a] and Na^+ appears more associated than K^+. Thus *K* in Scheme II is smaller for potassium than for sodium, while *k*′ is obviously much larger, producing the observed efficiency of KH for metalating ketones. In fact, if the aldol product 4-hydroxy-4-methyl-2-pentanone is

Table I
Kaliation of Ketones at 20°

Compd[a]	Registry no.	Time, min	Enolate yield,[b] %	% *less* substituted enolate[c]
	Methyl Ketones			
Acetone	67-64-1	1.5	90	
2-Heptanone	110-43-0	1.5	100	46
3-Methyl-2-butanone	563-80-4	1	101	88
		30 (−78°)[d]	98	>99
3,3-Dimethyl-2-butanone	75-97-8	5	97	
Cyclopropyl methyl ketone	765-49-5	1	100	100
	Methine Ketones			
Isobutyrophenone	611-70-1	12	97	
2,4-Dimethyl-3-pentanone	565-80-0	10	100	
	Cyclic Ketones			
Cyclopentanone	120-92-3	2	81	
Cyclohexanone	108-94-1	1.5	90	
2-Methylcyclohexanone	583-60-8	6	96	33
		30 (−78°)[d]	98	95
	α,β-Unsaturated Ketones			
Mesityl oxide	141-79-7	1	97	*e*
Carvone	99-49-0	20	35	*e*
Pulegone	89-82-7	7	98	*e*

[a] 25.0 mmol of ketone, 28–35 mmol of KH, 40–50 ml of THF solution. [b] Ketone recovered after quenching with water and acid, glpc. [c] Isomers trapped with trimethylchlorosilane and triethylamine. [d] Metalation with potassium bis(trimethylsilyl)amide (I) formed *in situ*. [e] Products appeared to be entirely the conjugated dienolate.

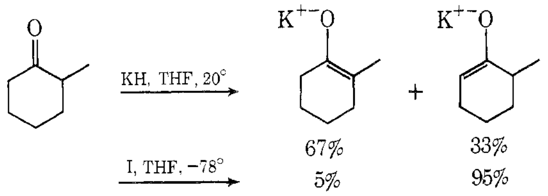
Scheme II



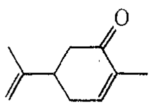
treated with KH, 2.0 equiv of hydrogen is evolved and acetone enolate is formed quantitatively; no mesityl oxide is observed.

Metalation with KH yields an equilibrium mixture of the potassium enolates directly. Sterically (kinetically?) controlled metalation may be achieved by first metalating bis(trimethylsilyl)amine (*vide supra*) *in situ* and thence adding the ketone at low temperature (Scheme III).

Scheme III



Metalation of α,β-unsaturated ketones proceeded smoothly with β,β-dialkyl structures yielding, as expected, the dienolate anion. Systems less hindered toward Michael addition such as carvone (IV) undergo substantial polymerization; methyl vinyl ketone and ethyl vinyl ketone were completely polymerized.

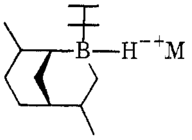


IV

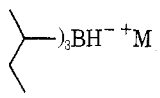
In no case was reduction observed to compete with metalation by KH.

Kaliations of ketones are summarized in Table I.

Hydride Transfer to Weak Lewis Acids. Considerable interest has been generated recently in complex borohydrides as reducing agents.[23] Certain of these have been prepared directly by reaction of organoboranes with LiH.[23c,24] However, increases in hindrance or decreases in Lewis acidity of the boron compounds and changes from ethers to hydrocarbon solvents inhibit or prevent reaction.[24a] The hindered trialkylborohydrides V and VI (M = Li)—highly stereoselective reducing agents—have been prepared only by indirect means.[23d,e]



V



VI

BX_3

VIIa, X = *sec*-Bu
b, X = O—*i*-Pr

Potassium hydride reacts rapidly with even very hindered and weakly acidic boron compounds in THF, providing the only direct, general method for quaternizing boron with hydride. Much of this activity is retained in hydrocarbon solvents as well. These results are summarized in Table II.

In contrast to the facile reactions of KH, NaH and LiH were sluggish or unreactive.[25] With VIIa, NaH reacted only 10% in 8 hr and LiH is inert.[26] With VIIb, both NaH and LiH are unreactive in THF at 25°, though reaction of NaH has been reported at high temperatures.[27]

Poisoning of KH. No systematic survey of poisoning agents has been made. Experience shows, however, that KH which has been exposed to atmospheric moisture tends to be less reactive and show induction periods in its reactions, possibly because of surface coating by KOH. Such samples can often be activated by stirring with a small amount of methyl iodide in THF. Trimethylchlorosilane is

Table II
KH Hydride Transfer to Boron Lewis Acids (BX_3)[a]

X	Registry no.	Solvent[b]	Temp, °C	Time, min	B–H yield, %
Et	97-94-9	THF	5–10	15[c]	100
Et		$PhCH_3$	20	30[c]	97
n-Bu	122-56-5	THF	20	60	101
i-Bu	1116-39-8	THF	20	60	96
i-Bu		$PhCH_3$	20	750	81
sec-Bu	1113-78-6	THF	20	60	100
i-PrO	5419-55-6	THF	20	60	100

[a] 25 mmol of BX_3 with 35–50 mmol of KH dispersed in the indicated solvent. [b] Concentration of BX_3 = 0.95–1.0 *M*; 0.65–0.70 *M* for (i-PrO_3)$_3$B. [c] BEt_3 added dropwise over 5 min with cooling.

a very effective poison and attempts to effect metalations in its presence (*e.g.*, to achieve trapping of kinetically generated anions) have uniformly proven unsuccessful. Similar results have been reported with NaH;[28a] in this case it was suggested that traces of alkoxide acted as a "carrier" in metalations, these being removed by the silylating agent. We feel this is unlikely as the poisoning effect remains even if the silylating mixture is replaced by fresh solvent. Possibly the poisoning represents a reduction of the Si–Cl bond, with the surface of the KH crystal being converted to KCl or a potassium silyl.[28b,c]

Handling of KH. Because of the much higher reactivity of KH compared to that of the widely used NaH, the rather cavalier treatment often accorded the latter is both unsuitable and hazardous. With reasonable precautions KH may be handled with both safety and ease; our experience is fully described in the Experimental Section.

Experimental Section

Storage and Transfer of KH. Potassium hydride has been obtained currently[29] as a dispersion in mineral oil containing 20–35% KH by weight.[30] Although pure KH is a white powder, most samples obtained were gray, presumably due to traces of unreacted potassium.[31] Potassium hydride reacts slowly with oxygen. We have stored it (a) in glass bottles or (b) in polyethylene bottles kept in inert atmosphere or sealed with varnish to prevent diffusion of oxygen.

Upon standing, KH segregates from the oil and with prolonged storage the material becomes compacted, requiring rather vigorous attack to achieve initial dispersion.[32]

Transfers of KH in oil may be made quickly in air without difficulty but for prolonged handling (*e.g.*, initial dispersing of the compacted mass) a glove bag (N_2 or Ar) is desirable. Routine transfers are performed directly from the storage container. Two holes just sufficient to accept 18–19 gauge hypodermic needles are punched in the polyethylene container near the screw cap. Through one hole a vigorous stream of dry nitrogen is introduced with a short needle, providing a backflush during transfer. The dispersion is transferred using a medicine dropper having a 2–3-mm orifice.[33] The container is then capped and purged with nitrogen, and the cap and holes are sealed with tape, paraffin, etc.

Utensils and glassware coated with KH–oil may be cleaned by rinsing with a 10% solution of an alcohol in hydrocarbon (*e.g.*, kerosene).

Caution! Under no conditions should KH–oil be directly placed in water or ignition may occur. Disposal of organic solvents containing even traces of KH in sinks will produce a fire.

Standardization of KH. A weighed sample of the KH dispersion (1–2 g) is placed in a flask equipped with a TFE-covered magnetic stirring bar, condenser, and injection port capped with a rubber sleeve stopper. The apparatus is purged with nitrogen and connected through traps to a gas-measuring device. The flask is immersed in a water bath and, with stirring, 20 ml of 2-butanol is added, dropwise at first until hydrogen evolution moderates. The KH present is determined by a standard gas law calculation of the hydrogen liberated (1.0 H_2 = 1.0 KH).

The resulting solution in the flask may be diluted with water and titrated to a phenolphthalein end point. Substantial excesses (>5%) of total base over hydride base (from gas evolution) indicate significant hydrolysis of the original KH sample.

Separation of KH from the Oil Matrix. The KH is placed in the apparatus described above, with a mercury bubbler replacing the gas-measuring device. Dry pentane, ether, or similar solvent[34] is added: 5–10 ml/g of dispersion. The mixture is stirred briefly and allowed to settle with occasional tapping, and the solvent–oil solution is removed with the syringe. Three such washings remove all but traces (<1%) of the oil. To facilitate removal of the solvent, an 18–20 gauge flat-tipped needle 8–10 in. long is used.[35] The solvent washed may contain traces of highly reactive KH fines and *must* be treated with a lower alcohol before disposal. Fine KH particles almost inevitably cause ignition if spent washes are disposed of in sinks, etc.

Residual solvent is removed under vacuum or with a stream of N_2 or Ar.

Potassium Pyrrolidide. In the apparatus described above was placed 25 mmol, 1.0 g dry basis, of KH; the oil was removed with pentane. To the dry KH was added 25 ml of pyrrolidine (distilled and dried over 4A molecular sieve). Reaction at 25° proceeded smoothly at a moderate rate, with hydrogen evolution ceasing at 95% of the theoretical amount (based on KH) in 2 hr. Yield of amide was 93% (based on KH, 98% based on H_2 evolved) by titration with 2,6-di-*tert*-butylphenol in benzene using triphenylmethane as an indicator (blood red → colorless). The alkamide was apparently largely insoluble in the pyrrolidine, the reaction mixture being a grayish slurry; addition of up to 75 ml of pyrrolidine did not appear to allow dissolution of the majority of the solid.

Addition of 20 mmol of bromobenzene to a suspension of potassium pyrrolodide "1 *M*" at 25–30°, followed by quenching with water, yielded after distillation 90% (based on bromobenzene) of *N*-phenylpyrrolidine.

Potassium Methylsulfinylmethide ("Dimsyl"). In the apparatus described above (125 ml flask) was placed 25 mmol, 1.0 g dry basis, of KH freed of oil with pentane as described above. The flask was cooled in a 10° water bath and 25 ml of dimethyl sulfoxide (dried over 4A molecular sieve) was added with stirring. Vigorous hydrogen evolution began immediately and was quantitative in minutes. The resulting solution was nearly clear and straw colored; the yield was 96% by titration with 2,6-di-*tert*-butylphenol in benzene.

Potassium Bis(trimethylsilyl)amide. Excess Metalating Agent. In the apparatus described above (125-ml flask) was placed 31.2 mmol, 1.25 g dry basis, of KH. After removal of oil, 20 ml of THF (dried over 4A molecular sieve) was added, followed by 25 mmol, 5.2 ml, of distilled bis(trimethylsilyl)amine with cooling (20°) and vigorous stirring. Hydrogen evolution was quantitative in 15 min.[36] After standing unstirred for 30 min, the slightly turbid base solution could be decanted from excess KH; several hours was required for complete settling of suspended matter.

Excess Substrate. The previous procedure was carried out using 25 mmol of KH and 35 mmol of bis(trimethylsilyl)amine. The resulting slightly turbid solution could be clarified by settling or anaerobic filtration through a thin pad of diatom filter aid; however, the turbidity has not affected any preparative uses of the amide solution.

In a similar manner, alkoxides and phenoxides were formed; 2,6-di-*tert*-butylphenol, a solid, was added slowly (vigorous hydrogen evolution) as a concentrated THF solution.

Potassium Enolate of 2,4-Dimethyl-3-pentanone. The ketone, 25 mmol/ml, was added to a suspension of 30 mmol, 1.2 g, of KH in 95 ml of THF at 20° with vigorous stirring. Hydrogen evolution was quantitative in 12–15 min; enolate yield was quantitative (by glpc after quenching with dilute HCl and addition of standard). A centrifuged sample of the enolate solution was free of ketone carbonyl by ir (1718 cm^{-1}) and showed an absorption for the enolate ion at 1604 cm^{-1}.

Potassium Enolate of 2-Methylcyclohexanone. Sterically–Kinetically Controlled Enolate Formation. Potassium bis(trimethylsilyl)amide was generated as described above (excess substrate procedure) from 27.5 mmol of KH and 30 mmol of distilled bis(trimethylsilyl)amine. The resulting solution, used directly without filtration, was cooled to −78° and 10 ml of a 2.5 *M* solution of 2-methylcyclohexanone in THF was added dropwise over 30 min with vigorous stirring. The yield of enolate was 95% (by glpc after quenching with dilute HCl and addition of standard); reaction of a sample of enolate solution with excess triethylamine–trimethylchlorosilane to trap the enolate[28a] revealed the enolate to be predominantly (95%) the *less* substituted isomer. Direct reaction of 2-methylcyclohexanone with KH at 20° yielded a 2:1 mixture containing chiefly the *more* substituted enolate isomer, the equilibrium mixture at 20–25°.[37]

Potassium Tri-*sec*-butylborohydride. In the apparatus described above (125-ml flask) was placed 35 mmol, 1.40 g dry basis, of KH, and the oil was removed with pentane. The KH was suspended in 20 ml of THF and 25 mmol, 6.0 ml, of pure tri-*sec*-butylboron was added in one portion with stirring. After 1 hr at 20° in a water bath, reaction was quantitative (by hydrolysis of a centrifuged sample). The product has a 1:1:1 ratio of K^+ (as total base) to H^- (as hydrogen after hydrolysis) to boron (as 2-butanol after oxidation with $NaOH-H_2O_2$[38]). The solution separated from excess KH exhibited a broad ir absorption at 2025 cm^{-1} (B–H str) absent in solutions of tri-*sec*-butylboron.

Similar results were obtained by adding a THF solution of 25 mmol of tri-*sec*-butylboron—prepared *in situ* by hydroboration[38] of excess 2-butene—to dry KH. The yield was 93%.

Either of the above solutions rapidly reduced cyclic ketones at 0° to −78° to yield alcohols of the *less* stable stereochemistry. Thus 2-methylcyclohexanone and 4-methylcyclohexanone yielded at 0° the corresponding alcohols quantitatively with >99% and 88% cis stereochemistry, respectively.

Potassium Triethylborohydride. To KH, 30 mmol, suspended in THF or toluene (*vide supra*) was added *dropwise*, with ice cooling, 25 mmol, 3.5 ml, of triethylboron (Ethyl Corp.; *caution!* spontaneously flammable in air) over 2–3 min with vigorous stirring. The mixture was allowed to warm to 20° over 30 min; the yield is quantitative. The ir spectrum of the THF solution separated from excess KH showed a broad absorption at 1975 cm^{-1} [39] with shoulders at 2010 and 2070 cm^{-1} (B–H str), absent in triethylboron.

The THF solution of potassium triethylborohydride rapidly reduced alkyl halides in the manner reported[23c] for the lithium analog.

Potassium Triisopropoxyborohydride. In the apparatus described above was placed 50 mmol, 2.0 g dry basis, of KH, and the oil was then removed with pentane. The KH was suspended in 30 ml of THF and 25 mmol, 5.8 ml, of freshly distilled triisopropyl broate[40] was added. After stirring for 30 min at 20–25°, the yield of the borohydride was quantitative; a centrifuged solution contained a 1:1:1 ratio of K^+ (as total strong base) to B (by titration[27] in the presence of mannitol) to H^- (as hydrogen liberated by hydrolysis with aqueous HCl).

The solution of potassium triisopropoxyborohydride reduced 2-methylcyclohexanone stereoselectively to the cis alcohol (95.5%) at −23°; even at 0° reduction of esters and alkyl halides was observed to be very slow or nonexistent.

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Registry No.—KH, 7693-26-7.

References and Notes

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(29) In the United States, KH is currently manufactured and supplied by Pressure Chemical Co., Pittsburgh, Pa., and by Alfa Inorganic Chemicals Division of Ventron Corp., Beverly, Mass. The material from the former appears to be somewhat more finely divided and reactive.

(30) Dispersions with greater than 40% by weight are too viscous for convenient handling.

(31) Reactivity and assay (±3%) appear unrelated to the degree of color; even dark grayish brown samples have been highly reactive, although the reaction product may be colored.

(32) A long-bladed screwdriver has proven the most efficient, if inelegant, tool for this purpose. Once dispersed, aggitation once or twice a month prevents hard compaction. A polyethylene- or TFE-covered magnet left in the container has proven excellent for achieving smooth dispersions.

(33) Syringes prove unsatisfactory due to "jamming" of the plunger by the KH powder.

(34) (a) Solvents obviously should be dry and free of protic materials. Moder-

ate amounts of unsaturated hydrocarbons appears to have no effect. (b) It is desirable that solvents have a low viscosity and density to facilitate settling of the KH particles. KH has a crystal density of 1.43 g cm^{-3}.

(35) (a) Available from the Hamilton Co., Whittier, Calif. (b) When using a flat-tipped needle, it is necessary to puncture the rubber-sleeve stopper with a regular needle first.

(36) Occasionally short induction periods have been observed especially with samples of KH that have been exposed to the atmosphere repeatedly. In such cases slower metalation (1 hr) has occurred.

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Kinetics and Mechanism for Hydrolysis of Substituted α,α-Dichlorotoluenes

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The rate of hydrolysis of α,α-dichlorotoluene and the corresponding *p*-chloro- and *p*-methyl derivatives in aqueous solution is independent of pH over the range 2–11. The reactivity of these substrates is very sensitive to the nature of polar substituents: the relative rates of hydrolysis of the *p*-chloro, unsubstituted, and *p*-methyl compounds is 0.6:1:78. Hydrolysis of these substrates exhibits values of entropy of activation in the range −8 to −13 eu. Salt effects on the rate of hydrolysis of α,α-dichlorotoluenes are small but hydrolysis is markedly retarded by addition of dioxane. Rate constants measured in 50% aqueous dioxane are 600–1000 times as small as those measured for the same substrates in water. Hydrolysis of these substrates is also subject to inhibition by both cationic and anionic surfactants: diminutions in rate between 10- and 100-fold are observed in the presence of 0.05 *M* surfactants. These data corroborate a mechanism of hydrolysis involving rate-determining unimolecular carbon–chlorine bond cleavage.

Mechanism and catalysis for hydrolysis of acetals and ketals[1-3] and related species[4,5] have been vigorously studied. As a consequence, a substantial body of experimental information is available on which to base conclusions concerning mechanism and to found predictions concerning the behavior of novel compounds in the same class. In contrast, rather little study of the hydrolysis of α,α-dichlorotoluenes has been undertaken, although there is substantial reason to believe that these reactions occur with rate-determining unimolecular cleavage of a carbon–chlorine bond.[6-8] However, little information is available concerning structure–reactivity relations, solvent effects, salt effects, and effects of ionic surfactants for these reactions. We report here results of an investigation of the kinetics of hydrolysis of substituted α,α-dichlorotoluenes in aqueous solution and other media designed to provide such information.

Experimental Section

Materials. α,α-Dichlorotoluene, *p*-methyl-α,α-dichlorotoluene, and *p*, α, α-trichlorotoluene were synthesized from the appropriate benzaldehydes and phosphorus pentachloride as previously described.[9] Ir and pmr spectra revealed no detectable impurities in these preparations. 1,4-Dioxane was obtained from the Eastman-Kodak Co. and was purified by distillation and passage through a column of neutral aluminum oxide (M. Woelm). Sodium dodecyl sulfate was obtained from the British Drug Houses Ltd., and was purified as previously described.[10] Dodecyltrimethylammonium bromide and hexadecyltrimethylammonium bromide were purified samples donated by the Department of Chemistry, Indiana University. All other reagents were of the best grade commercially available. Distilled water was employed throughout.

Kinetic Measurements. Hydrolysis of substituted α,α-dichlorotoluenes was followed spectrophotometrically by monitoring the appearance of the appropriate benzaldehyde as a function of time. Substrate concentrations near 10^{-4} *M* were employed. All measurements were made with a Zeiss PMQ II spectrophotometer equipped with a cell holder through which water from a thermostated bath was continuously circulated. First-order rate constants were calculated from semilogarithmic plots of the difference between infinite time optical density and optical density at specific times against time. Excellent first-order behavior was observed for all reactions studied. Except for those reaction mixtures containing ionic surfactants, for which additional electrolytes were not added, ionic strength was maintained constant at 0.5 through addition of calculated quantities of KCl. Values of pH were measured employing a Radiometer PHM 26 pH meter.

Activation parameters were calculated from rate constants measured at 20, 30, 40, and 50°. In accord with previous observations,[7] the energy of activation was found to be dependent on temperature and each value was calculated from the following expression[7]

$$E_{act}^{obsd} = [RT_aT_b/(T_b - T_a)] \ln (k_b/k_a) \qquad (1)$$

in which k_a and k_b refer to rate constants measured at T_a and T_b, respectively. These values of the energy of activation were subsequently refined using the best value of E_0 and c, obtained by the method of least squares, in which c is the temperature dependence of the activation energy, dE/dT, and E_0 is defined by

$$E_{act}^{obsd} = E_0 + c(T_a + T_b)/2 \qquad (2)$$

Values of entropy of activation were then calculated from

$$\ln k_a = \ln (k/h) + \ln (T_a + T_b)/2 + 1 + \Delta S^*/R - E_{act}/RT_a \qquad (3)$$

in which k and h are the Boltzman and Planck constants, respectively.

Equilibrium constants for the association of the α,α-dichlorotoluenes with micelles formed from ionic surfactants were estimated from the dependence of rate of hydrolysis on surfactant concentration employing the following expression[11]

$$1/(k_a - k_{obsd}) = 1/(k_a - k_m) + 1/(k_a - k_m)[N/K(C_d - \mathrm{cmc})] \qquad (4)$$

in which k_a is the rate constant observed in aqueous solution, k_{obsd} is the rate constant observed at each surfactant concentration, k_m is the rate constant observed at saturating concentrations of surfactant, N is the aggregation number of the micelle, C_d is the concentration of surfactant, cmc is the critical micelle concentration, and K is the equilibrium constant of interest. A value of N equal to 70 was employed in the calculations.

Results

First-order rate constants for hydrolysis of α,α-dichlorotoluene and the *p*-methyl and *p*-chloro derivatives in aqueous solution at 30° and ionic strength 0.5 were mea-