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X-ray Crystal Structures of Lithium, Sodium, and Potassium Enolates of Pinacolone

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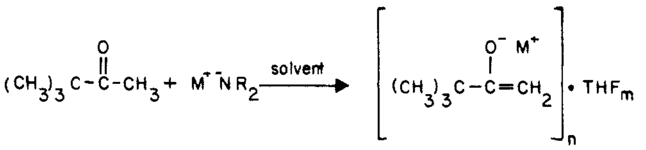
Abstract: Reaction of 3,3-dimethyl-2-butanone (pinacolone) with alkali amide bases yields crystalline enolates. These compounds were subjected to single-crystal X-ray diffraction analysis. The lithiated enolate aggregates as an unsolvated hexamer, the sodium enolate aggregates as a tetramer solvated by *unenolized* ketone, and the potassium derivative aggregates as a hexamer solvated by THF. Comparison of the crystal structures with one another and with other alkali metal enolate structures reveals subtle differences. These structural differences may be useful for explaining reactivity differences and may have potential utility in organic synthesis.

Ketone enolates associated with different group Ia metal cations exhibit distinct reactivity differences.[1] Perhaps these reactivity differences can be correlated with structural differences among the various enolates. Hence, as part of our continuing investigation into the crystal structures of synthetically important organic nucleophiles, we now provide the first X-ray crystal structures of a series of group Ia alkali metal ketone enolates.

Lithium ketone enolates exist as aggregates in solution.[2] Since no X-ray crystal structures of unactivated lithium ketone enolates existed prior to 1981, comparisons between aggregation in solution and the aggregation of crystalline metal enolates had been impossible. In 1981, the first X-ray crystal structure determination[3] of two lithium ketone enolates confirmed that the same tetrameric aggregate formed in solution is also formed in the solid.

Colligative property measurements of solutions of many organolithium compounds reveal the presence of aggregates.[4] NMR studies also prove useful for elucidating the aggregation behavior of organolithium compounds in solution.[5] Recent X-ray crystal structure determinations of synthetically important organolithium derivatives confirm the presence of aggregates in the solid state.[6]

Scheme I



$$(CH_3)_3C\text{-}\overset{O}{\overset{\|}{C}}\text{-}CH_3 + M^+\,{}^-NR_2 \xrightarrow{\text{solvent}} \left[(CH_3)_3C\text{-}\overset{O^-\ M^+}{\overset{|}{C}}{=}CH_2\right]_n \cdot THF_m$$

M	R	solvent	compd	*n*	*m*
Li	$CH(CH_3)_2\cdot THF$	heptane	1	4	4
Li	$CH(CH_3)_2$	heptane	2	6	0
Na	$Si(CH_3)_2$	heptane	3	4	0
K	$Si(CH_3)_2$	heptane/THF	4	6	6

Hence, it now seems probable that solid-state aggregates closely resemble the solution aggregates for many organolithium compounds. The similarity between the solid state and the solution aggregates is likely to extend to other group Ia alkali metal ketone enolates.

We selected *tert*-butyl methyl ketone (pinacolone) as a substrate for this investigation because X-ray crystal structures are now reported for both unsolvated[7] and THF-solvated[3] lithium enolates of this ketone. Its alkali metal enolates have also been studied by IR spectroscopy.[8] Comparisons among the two lithium pinacolone enolate crystal structures,[3,7] the sodium enolate, and the potassium enolate crystal structures of this ketone will be given. None of the pinacolone enolate crystal structures are isomorphous.

Results

Slow addition of pinacolone to a well-stirred suspension of an alkali metal amide base yields the crystalline enolates shown in Scheme I. The reactions in Scheme I follow the general procedure described by Lochmann.[8]

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(1) See, for example: (a) Evans D. A. "Asymmetric Synthesis"; Morrison, J. D., Ed.; Academic Press: New York, 1984; Vol. 3, Part B, pp 2–110. Heathcock, C. H. In "Asymmetric Synthesis"; Morrison, J. D., Ed.; Academic Press; New York, 1984; Vol. 3, Part B, pp 111–212. (c) le Noble, W. J.; Morris, H. F. *J. Org. Chem.* **1969**, *34*, 1969. (d) le Noble, W. J.; Puerta, J. E. *Tetrahedron, Lett.* **1966**, 1087. (e) Brieger, G.; Pelletier, W. M. *Tetrahedron. Lett.* **1965**, 3555. (f) Chatterjee, A.; Banerjee, D.; Banerjee, S. *Tetrahedron Lett.* **1965**, 3851. (g) Bottom, F. H.; McQuillin F. J. *Tetrahedron Lett.* **1967**, 1975. (h) Kurz, A. L.; Beletskaya, I. P.; Macias, A.; Reutov, O. A. *Tetrahedron. Lett.* **1968**, 3679. (i) Kornblum, N.; Seltzer, R.; Haberfield, P. *J. Am. Chem. Soc.* **1963**, *85*, 1148.

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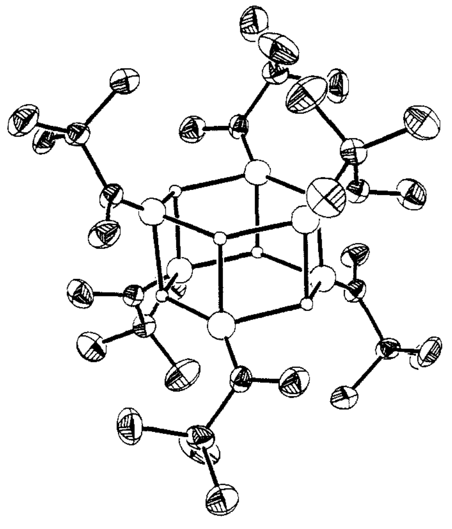

Figure 1. Unsolvated hexameric aggregate of lithium enolate of pincolone; large circles = oxygen, small circles = lithium.

The amide bases employed in Scheme I were obtained as follows. Addition of *n*-butyllithium to diisopropylamine at 0 °C in pentane produces lithium diisopropyl amide (LDA). We crystallized the LDA, final concentration ≅ 1.3 M, at −20 °C and washed it several times with pentane to remove traces of unreacted starting materials. Sodium hexamethylsilazane was prepared (NaHMDS) from bis(trimethylsilyl)amine and sodium amide according to the Wannagat procedure.[9] We utilized a commercial sample of crystalline potassium hexamethyldisilazane (KHMDS) directly as supplied.[10]

Low-temperature recrystallization of LDA from THF, as reported in the literature,[11] yields a crystalline 1:1 THF–LDA complex.[12] Pinacolone enolate formation in pentane with recrystallized, THF-solvated LDA produces THF-solvated, lithium enolate crystals **1** (Scheme I). These pinacolone enolate crystals are exactly the same as those obtained by Seebach, Dunitz, et al.[13] Thus, a solvating THF molecule remains strongly bound to lithium once introduced into the reaction. However, utilization of unrecrystallized LDA for lithium enolate formation provides the unsolvated lithium enolate of pinacolone **2**.[7]

The pinacolone/NaHDMS reaction was surprising because the crystals, **3**, from this reaction contained a molar equivalent of *unenolized* ketone (vide infra). We were unsuccessful in growing single crystals of the potassium enolate of pinacolone by addition of the ketone of KHMDS in heptane or toluene. Although we obtained a solid precipitate of potassium enolate in this reaction, this material was not suitable for X-ray diffraction analysis. Inclusion of a molar equivalent of THF in the reaction overcame this problem. Thus, slow addition of a heptane solution of pinacolone/THF (molar ratio ≅ 1:1) to a stirred suspension of KHMDS was followed by addition of a small excess THF to dissolve any remaining salts. This experimental protocol led to single crystals of THF-solvated potassium enolate **4** suitable for diffraction analysis.

The reactions in Scheme I were carried out at 0 °C. During the course of all of the reactions, most of the insoluble metal amide bases gradually disappeared. Well-shaped crystals grew when the reaction mixtures were placed in a freezer at −28 °C overnight.

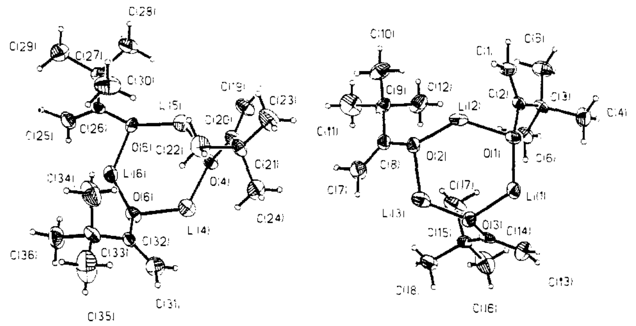

Figure 2. Crystallographic asymmetric unit of Li^+pin^-. Thermal ellipsoids are plotted at the 50% probability level.

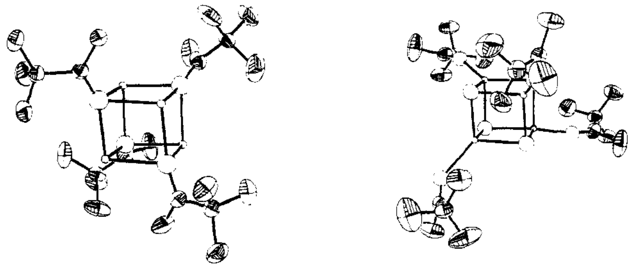

Figure 3. Sodium enolate of pincolone; large circles = oxygen, small circles = sodium. (a) Left-hand plot shows only the pincolone residues. (b) Right-hand plot shows only the unenolized ketones solvating the sodium atoms. The actual structure is a composite of these two partial structures.

Single crystals of compounds **2**–**4** were transferred to the diffractometer and kept below −100 °C in a stream of dry N_2 during diffraction data collection.

Table I provides a summary of the crystallographic parameters for compounds **2**–**4**. Direct methods[14] and iterative Fourier difference syntheses solved the crystal structures. Repetition of the latter procedure located all atoms in the structures. All non-hydrogen atoms were refined anisotropically.[15]

Discussion

The unsolvated lithium enolate of pinacolone, Li^+pin^-, compound **2**, forms a hexameric aggregate depicted in Figure 1. Details of this structure were previously reported by us.[7] The bottom half of the hexamer is related to the top half by a crystallographic inversion center located at the center of the hexagonal prism. Thus, the hexamer depicted does not correspond to the true crystallographic asymmetric unit. The crystallographic asymmetric unit consists of two independent half hexamers, each of which sits near a crystallographic inversion center. A plot of the crystallographic asymmetric unit of Li^+pin^- with atom labels is given in Figure 2.[15]

All six crystallographically independent lithiumn enols in Figure 2 bear a close resemblance to one another. Hence, enough similarity exists among the crystallographically independent enols displayed in Figure 1 so that this hexameric aggregate exhibits approximate S_6 symmetry.

Each oxygen atom of the hexamer in Figure 1 coordinates to three lithium atoms. Each C=C double bond is approximately anti periplanar to one lithium atom. The conformation about the C–O σ bonds is such that a 1:1 correspondence exists between each of the six C=C π bonds and the six peripheral (i.e., approximately square) faces of the prism. As noted in our previous communication,[7] it is possible to consider electron donation from the C=C π bonds in this structure to a fourth unoccupied coordination site on the lithium atoms because of the relatively short interatomic distances between Li and the sp^2-hybridized carbons.

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(9) Wannagat, U.; Niederprüm, H. *Chem. Ber.* **1961**, *94*, 1540.

(10) Solid KHMDS was obtained from Callery Chemical Co., Callery, PA 16024. Crystallization of this material from toluene solutions available from the same source yields the toluene solvate of the amide; see: Williard, P. G. *Acta Crystallogr., Sect. C,* submitted for publication.

(11) Lochmann, L.; Lim, D. *J. Organomet. Chem.* **1973**, *50*, 9.

(12) A tentative structure for the LDA–THF complex is proposed based upon aggregation studies, see ref 4a, pp 1982–1983. This structure is now confirmed by X-ray crystallography: P. G. Williard, unpublished results.

(13) These crystals were prepared from hydrocarbon solution following the general procedure outlined except that LDA recrystallized from THF was employed as the base. The crystals were identified by comparison of their crystallographic unit cell parameters with those reported in ref 3.

(14) All crystallographic calculations utilized the SHELXTL 4.1 programs (Nicolet XRD Corp., Madison, WI).

(15) Complete crystallographic parameters have been deposited with the Cambridge Crystallographic Data Center, Lensfield Rd., Cambridge, England.

Table I. Crystallographic Parameters for Compounds **2–4**

	2	**3**	**4**
chemical formula	$C_6H_{11}OLi$	$C_6H_{11}ONa{\cdot}C_6H_{12}O$	$C_6H_{11}OK{\cdot}C_4H_8O$
formula wt	106.11	222.34	210.39
cryst asymmetric unit	$[C_6H_{11}OLi]_6$	$[C_6H_{11}ONa{\cdot}C_6H_{12}O]_2$	$[C_6H_{11}OK{\cdot}C_4H_8O]_3$
crystal class	triclinic	trigonal	triclinic
space group	$P\bar{1}$	$P3_121$	$P\bar{1}$
unit cell parameters[a]			
a, Å	11.649 (4)	12.803 (5)	11.802 (5)
b, Å	11.814 (5)	12.803 (5)	13.789 (7)
c, Å	17.139 (8)	29.776 (14)	13.899 (7)
α, deg	80.64 (3)	90.00	59.84 (3)
β, deg	74.09 (3)	90.00	74.43 (4)
γ, deg	66.43 (3)	120.00	81.94 (4)
vol, Å^3	2075.3 (1.4)	4227.0 (1.2)	1886.21 (1.4)
z	2	6	2
calcd density, g/cm^3	1.02	1.05	1.11
data collection parameters[b]			
scan type	$\theta:2\theta$	$\theta:2\theta$	$\theta:2\theta$
scan range	$3.5° \leq \theta \leq 45°$	$3.5° \leq \theta \leq 45°$	$3.5° \leq \theta \leq 45°$
temp, °C	$\cong -100$	$\cong -100$	$\cong -100$
total data collected	5352	2192	5227
unique data observed	3491	2062	4237
Final agreement factors[c]			
parameters refined	470	271	352
R	0.0781	0.0515	0.0533
R_w	0.0883	0.0627	0.0580

[a] On the basis of least-squares refinement of 25 centered reflections in the range $25° \leq \theta \leq 27°$. [b] X-radiation = Mo Kα (λ = 0.71069 Å). [c] $R_w = [\sum(w\Delta^2)/\sum(wF_o^2)]^{1/2}$; $\Delta = |F_o - F_c|$ and the weighting scheme is $w = 1/[\sigma^2(F_o) + 0.0002F_o^2]$.

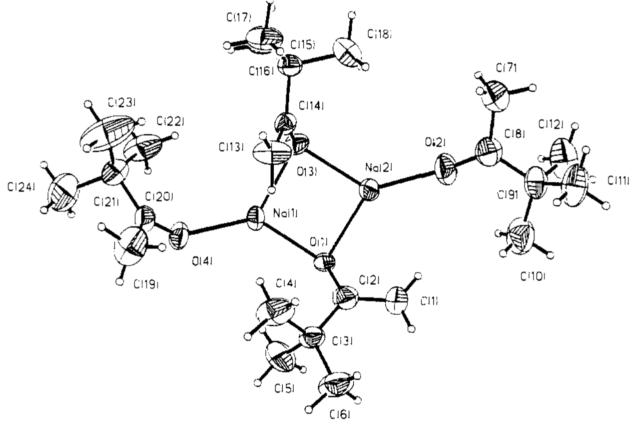

Figure 4. Crystallographic asymmetric unit of Na$^+$pin$^-$. Thermal ellipsoids are plotted at the 50% probability level.

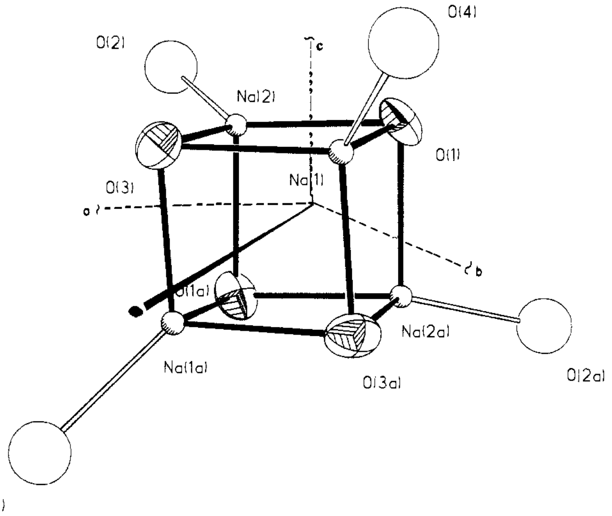

Figure 5. Tetrameric cube of sodium and oxygen atoms showing relative orientation with respect to crystallographic diad axis. Large open circles are oxygen atoms of the solvating ketones. Second atoms generated by the transformation ($y,x-z$).

The sodium enolate of pinacolone, Na$^+$pin$^-$ compound **3**, aggregates as a tetramer. This tetramer is a cubic cluster composed of four enolized ketone molecules, four sodium atoms, and four *unenolized* solvating ketones. Figure 3 depicts the tetrameric aggregate as two partial structures. Figure 3a shows the Na–O cube along with four enolized ketones. Each sodium atom is coordinated by three enol oxygen atoms and one ketone oxygen atom (not shown in Figure 3a) all at similar distances $\cong$ 2.25 Å. Figure 3b shows the Na–O cube from the same perspective minus the enolized ketone moieties but including the unenolized solvating ketones. These partial structures are plotted separately for clarity.

The tetrameric aggregate of the sodium enolate of pinacolone in Figure 3 is chiral. Its symmetry includes a crystallographic twofold rotation axis passing through the centers of the front and rear faces of the cube in the perspective shown. The crystallographic asymmetric unit consists of a species whose molecular formula is $[(C_6H_{11}ONa){\cdot}(C_6H_{12}O)]_2$[15] (Figure 4). This asymmetric unit corresponds to either the right or left halves of the cubes in Figure 3.

Figure 5 illustrates the approximate orientation of the Na$^+$pin$^-$ tetramer with respect to a crystallographic diad axis. Only the sodium and oxygen skeleton is shown in Figure 5. Since this crystal belongs to an enantiomorphous space group, i.e., $P3_121$, crystallization effects spontaneous resolution of the tetrameric aggregate.[16]

An interesting comparison exists between the sodium-containing tetramer shown in Figure 3 and the tetrameric, THF-solvated lithium enolate of pinacolone (see Figure 1 in ref 3). The Seebach–Dunitz tetramer is different from the tetramer depicted in Figure 3 because of a conformational difference about the C–O bonds. In both tetramers the terminal methylene carbons of the enolized ketones are roughly antiperiplanar to one of three alkali metal atoms. If rotation about the enol C–O bond is restricted and if the C=C π bond remains antiperiplanar to a metal atom, a total of six conformational isomers are possible for such cubic

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(16) Spontaneous resolution is not uncommon. It has been estimated "...that for the general run of organic compounds...the frequency...may be estimated to be in the range 5 to 10%". (Cf.: Jaques, J.; Collet, A.; Wilen, S. H. In "Enantiomers, Racemates and Resolutions"; J. Wiley & Sons: New York, NY, 1981; pp 43–88.) This process is likely to be overlooked in most cases where a crystal structure determination is not performed on reaction products derived from racemic or achiral starting materials. As a rough confirmation of the estimate given above, of 30 simple organic compounds prepared in the first author's lab and investigated crystallographically within the past year, four (ca. 13%) of these have crystallized as conglomerates.

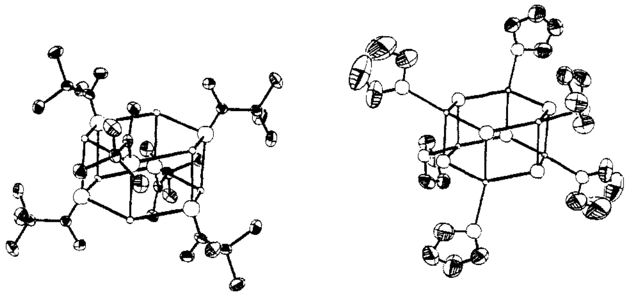

Figure 6. Potassium enolate of pincolone; large circles = oxygen, small circles = potassium. (a) left-hand plot shows only pinacolone residues. (b) Right-hand plot shows only the solvating THF molecules. The crystal is a composite of these two structures.

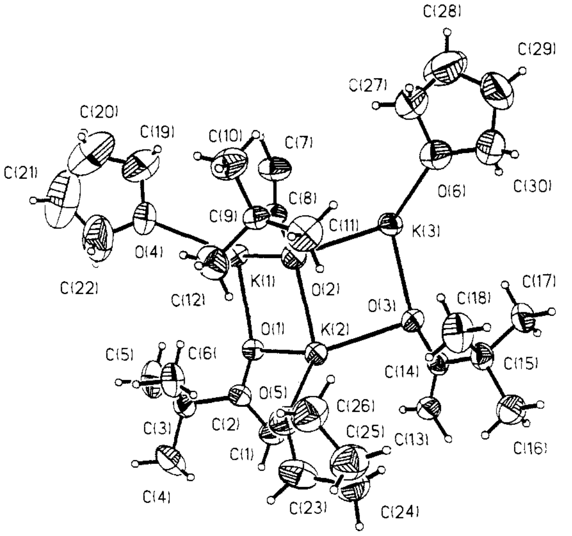

Figure 7. Crystallographic asymmetric unit of K$^+$pin$^-$. Thermal ellipsoids are plotted at the 35% probability level.

tetramers. Three of these isomers are chiral; three are achiral.

For the THF-solvated lithium tetramer[3] an achiral aggregate with approximate S_4 symmetry was observed, whereas the Na$^+$pin$^-$ enolate depicted in Figures 3 and 5 exhibits only C_2 symmetry. Hence, the Na$^+$pin$^-$ aggregate represents one of the three chiral isomers. Of course facile rotation about the C–O bond or disaggregation and reformation could interconvert all six possible isomers. Presently it is not known whether such equilibration takes place or how fast this might occur in solution.

The potassium enolate of pinacolone crystallizes as a THF solvated hexamer. All atoms in the crystallographic asymmetric unit were precisely located with the exception of one disordered THF molecule.[17] Two partial structures are presented (a and b in Figure 6) for ease to viewing but it should be understood that the aggregate is a composite of both structures. Both plots include the hexagonal prism formed by the enol oxygen atoms and the potassium cations. One plot (Figure 6a) includes only the enolized ketone species and excludes the solvating THF molecules, whereas the other plot (Figure 6b) excludes the pinacolone residues but includes the THF's of solvation.

Each potassium atom in Figure 6 coordinates to three enol oxygen atoms and one oxygen of a THF. All K–O bond lengths are similar, approximately 2.67 Å. The crystallographic asymmetric unit corresponds to either the front or the back half of the hexagonal prisms shown in Figure 6. The chemical formula of the crystallographic asymmetric unit is $[(C_6H_{11}OK)\cdot(C_4H_8O)]_3$. A labeled plot of this species is given as Figure 7.[15] The three crystallographically independent enols of this enolate are nearly identical, thus an approximate S_6 axis passes through the centers of the hexagonal faces of the prism in Figure 6.

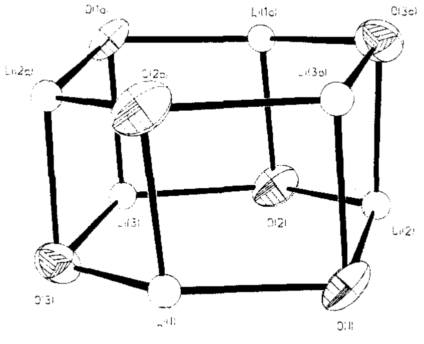

Figure 8. Lithium oxygen skeleton of Li$^+$pin$^-$. Second atoms generated by the transformation (1.0 − x, 2.0 − y, −1.0 − z).

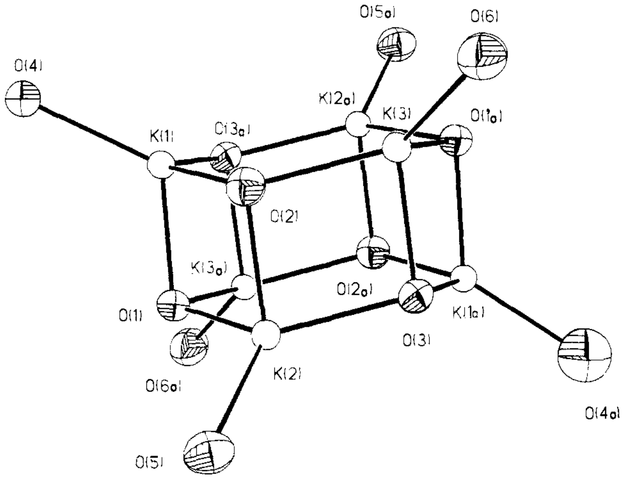

Figure 9. Potassium oxygen skeleton of K$^+$pin$^-$. Oxygen atoms of the solvating THF's also shown. Second atoms generated by the transformation (2.0 − x, 2.0 − y, 1.0 − z).

It is curious that the skeleton of the lithium and the potassium enolates in Figures 1 and 6 is a hexagonal prism but the sodium enolate is not. There is no reason to expect that aggregation as a hexamer is limited exclusively to lithium or potassium cations,[18] since hexameric (and nonameric) aggregates were reported by Weiss for sodium *tert*-butoxide in the solid state.[19] Thus it should be possible to obtain crystalline, hexameric aggregates of sodium ketone enolates too. We believe that we have recently prepared a hexameric, THF-solvated sodium enolate of pinacolone. Determination of the unit cell parameters of this substance (crystal class = trigonal; unit cell volume = 3607.7 Å^3) strongly suggests an aggregation state with a modulus of 3. Unfortunately it has not been possible to collect a complete set of diffraction data for this species due the marked diminution of the reflection intensities beyond sin θ/λ = 0.364.[20]

Plots depicting the two hexagonal prisms formed by the enol oxygen atoms and the metal cations of the lithium and of the potassium enolates are given in Figures 8 and 9, respectively. Detailed comparison of these two skeletons reveals significant differences in addition to the expected difference in metal–oxygen bond lengths. The six atoms forming either hexagonal face of the lithiated prism in Figure 8 are roughly coplanar (i.e, deviation of all six atoms by <0.1 Å from the best plane through each face). However, the six atoms forming the hexagonal faces of the prism in Figure 9 are definitely not coplanar. The plane defined by three oxygen atoms in the same hexagonal face of the structure in Figure

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(17) A sequence of four closely spaced but distinct THF molecules were located at the site of disorder (i.e., C(19–C(20)–C(21)–C(22)) by Fourier difference syntheses. Only the most prominent of these was included in the final refinement of independent variables.

(18) The hexagonal prism structure has also recently been reported for synthetic Fe_6–S_6 clusters, cf.: Coucouvanis, P.; Kanatzidis, M. G.; Dunham, W. R.; Hagen, W. R. *J. Am. Chem. Soc.* **1984**, *106*, 7998 and references therein.

(19) (a) Greiser, T.; Weiss, E. *Chem. Ber.* **1977**, *110*, 3388. (b) Davies, J. E.; Kopf, J.; Weiss, E. *Acta. Crystallogr.* **1982**, *B38*, 2251.

(20) This observation is indicative of extensive disorder in the crystals, and we feel that the solvating THF's are most likely disordered.

Table II. Average Distances and Angles for the Monomeric Enol in Figure 10

metal	Li	Na	K	Li
crystal structure	Figure 1	Figure 3	Figure 6	ref 2
aggregation state	(n = 6)	(n = 4)	(n = 6)	(n = 4)
crystallographically independent enols	(y = 6)	(y = 2)	(y = 3)	(y = 4)
av[a] bond lengths				
C(1)–C(2)	1.330 (6)	1.358 (6)	1.350 (4)	1.34[d]
C(2)–C(3)	1.526 (8)	1.514 (8)	1.501 (6)	
C(2)–O(1)	1.342 (6)	1.308 (4)	1.306 (4)	1.35[d]
O(1)–M(1)	1.851 (9)	2.241 (2)	2.568 (2)	1.94[d]
O(1)–M(2)	1.949 (9)	2.332 (4)	2.661 (3)	1.99[d]
O(1)–M(3)	1.953 (10)	2.330 (3)	2.649 (2)	1.99[d]
av[a] bond angles				
M(1)–O(1)–M(2)	114.4 (4)	88.4[b]	94.7 (1)	
M(1)–O(1)–M(3)	84.6 (4)	89.3 (1)	95.4 (1)	
M(2)–O(1)–M(3)	82.2 (4)	87.2[b]	115.4 (1)	
M(1)–O(1)–C(2)	141.9 (4)	149.4[b]	154.7 (2)	
M(2)–O(1)–C(2)	93.1 (4)	109.8[b]	96.8 (2)	
M(3)–O(1)–C(2)	126.0 (4)	114.8[b]	99.4 (2)	
O(1)–C(2)–C(1)	121.8 (5)	122.8 (5)	122.1 (4)	
O(1)–C(2)–C(3)	115.3 (4)	117.2 (4)	115.1 (3)	
C(1)–C(2)–C(3)	123.0 (4)	120.0[b]	122.8 (3)	
av[a] dihedral angles				
C(1)–C(2)–O(1)–M(1)	173.1[c]	150.5[c]	174.7[c]	
C(1)–C(2)–O(1)–M(2)	41.3[c]	31.7[c]	58.5[c]	
C(1)–C(2)–O(1)–M(3)	40.9[c]	64.2[c]	58.7[c]	

[a] The values reported are mean values of (y) independent measurements for each structure and the numbers in parentheses are the root mean square of the standard deviations of these values. [b] The two values used to compute this mean are similar but differ by considerably more than their standard deviations. [c] Values are the mean absolute value of the dihedral angles. [d] Values taken from ref 3.

9 is displaced by roughly 0.28 Å towards the center of the hexagonal prism relative to a plane defined by the corresponding potassium atoms. Thus, the slight distortion of the hexagonal faces of the prism in Figure 9 resembles a chair conformation of a cyclohexane ring. Closer scrutiny of the skeleton in Figure 8 reveals a very slight chairlike distortion too.

Further comparison between the lithium pinacolone aggregate (Figure 1) with the potassium aggregate (Figure 6) reveals a conformational difference about the enolic C–O bonds in these two hexamers. In the lithiated hexamer depicted in Figure 1, each of the six peripheral faces of the hexagonal prism is capped by a unique methylene group. This conformation is completely different from that depicted in Figure 6 where the terminal methylene groups of the enols are positioned over the two hexagonal faces rather than over the six peripheral faces of the prism. Thus, hydrophobic *tert*-butyl groups surround the periphery of the hexagonal prism in Figure 6.

A molecular model of the hexameric potassium enolate depicted in Figure 6a clearly reveals six pockets whose size conveniently allows entry of six solvating THF molecules. Conformational change of this THF-solvated aggregate requires loss of the solvating THF's and cooperativity among the enols or complete dissociation of the aggregate.

THF solvation of the lithium pinacolone enolate[2,3] leads to a tetramer rather than the hexamer depicted in Figure 1. These different aggregation states of the lithium enolates of pinacolone may be due to steric considerations. Molecular models reveal that the lithiated tetramer in ref 3 exhibits a greater steric ability to accommodate the solvating THF molecules than the lithiated hexamer in Figure 1. Steric crowing of solvating THF molecules in a hexagonal prism becomes much less important in the potassium enolate (Figure 6) because of the increase in the O–K bond lengths (av = 2.67 Å) relative to O–Li bonds (av = 1.95 Å).

Average bond lengths and angles are tabulated for all of the crystallographically independent pinacolone enols in Table II.[21] The numbering scheme in Table II refers to the generalized structure depicted in Figure 10 where M represents an alkali metal atom.

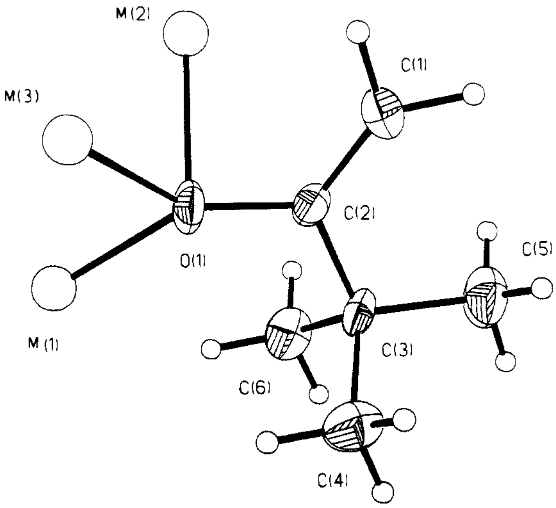

Figure 10. Representative monomeric enol of pinacolone.

Some interesting trends are evident in Table II. The C(1)–C(2) bond roughly bisects the M(2)–O(1)–M(3) bond angle in all cases. However, a considerable difference exists among the magnitudes of the C–O–M bond angles in the individual enols. Most noteworthy is the significantly larger bond angle observed for C(2)–O(1)–M(1) compared with the other two C–O–M bond angles. Perhaps the increase in this angle is due to the *tert*-butyl group attached to C(2) since this bulky group is roughly syn periplanar to M(1). Note also that in all four compounds the O(1)–M(1) bond is approximately 0.1 Å shorter than the other O–M bonds. In all of the enols, the C(3)–C(5) σ bond is syn to the C(1)–C(2) π bond as anticipated from MO arguments.[22] Because of the inequality among the three M–O–M bond angles and the three C–O–M angles, a Newman projection along the O(1)–C(2) axis of these enols provides a misleading representation for discussing the geometry of enolate anions and we suggest that it should not be used.

An obvious trend in Table II is the relative increase in the O–M bond lengths as the metal cation changes from Li to K. The increases are all in line with the differences in ionic radii of the alkali metal cations.[23] It is not obvious that the aggregates of

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(21) The average bond lengths and angles are simple arithmetic means for all crystallographically independent measurements of the same parameter.

(22) Hehre, W. J.; Salem, L. *J. Chem. Soc., Chem. Commun.* **1973**, 754.

(23) Wyckoff. R. "Crystal Structures", 2nd. ed.; J. Wiley & Sons; New York, 1968; Vol. 4, p 524.

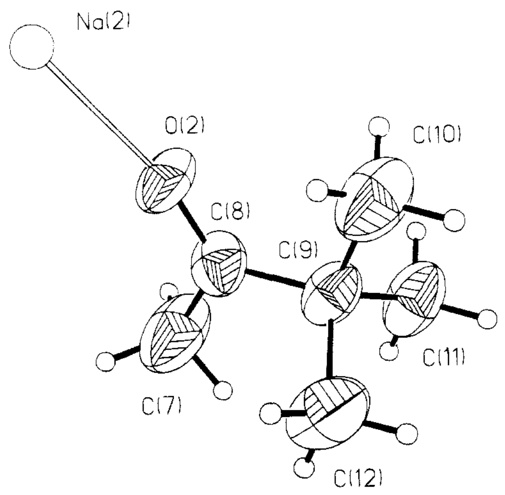

Figure 11. Plot of one of two crystallographically independent ketones of solvation of the Na$^+$pin$^-$ aggregate.

these enolates owe their thermodynamic stability solely to electrostatic interactions. Electrostatic interactions alone imply a decreased stability of the potassium aggregate relative to the lithium complex because of the increased interatomic distances. Hence, evaluation of the stabilization of these aggregates based upon a simple point charge model utilizing geometric considerations may not provide a useful estimate of the relative potential energies.

Figure 11 provides a plot of one of the two crystallographically independent molecules of unenolized ketone found in the Na$^+$pin$^-$ aggregate. The skeleton of this simple ketone is unexceptional. The C=O bond length (1.21 Å) is normal and C(10) is nearly eclipsed with the C=O bond as expected. The coordinate bond between the ketone oxygen, O(2), and the sodium atom, Na(2), is of length 2.285 (9) Å. This bond length is virtually identical with the other Na–O bonds which make up the basic Na$^+$pin$^-$ cube in Figure 5. The similarity in bond lengths seems to indicate that the interactions between a sodium atom and the oxygen atoms of either an enolized or an unenolized ketone are roughly identical in this aggregate.

It is notable that a stoichiometric amount of unenolized ketone remains unreacted in the presence of the highly nucleophilic sodium enolate. A pinacolone-solvated lithium enolate of 2,4,6-trimethylacetophenone reported is a stable intermediate although its structure was not determined.[3]

The torsion angles about the O(2)–C(8) bond for the ketone depicted in Figure 11 are 84° for Na(2)–O(2)–C(8)–C(7) and 96° for Na(2)–O(2)–C(8)–C(9). Similar torsion angles are found in the crystallographically independent ketone. A difference between the two crystallographically distinct unenolized ketones in this aggregate is exhibited for the bond angle represented by Na(2)–O(2)–C(8). In the ketone depicted, this angle is 164.7 (3)°, but it is 143.3 (4)° in the independent ketone. Such a large angular difference suggests a rather nondirectional interaction of the sodium atoms with the carbonyl oxygens.

The general angle approach of the electrophilic sodium atom toward the nucleophilic carbonyl oxygen in the Na$^+$pin$^-$ aggregate seems to fit with that proposed by calculation.[24] It remains to be seen whether a directional preference of electrophiles for carbonyl oxygen atoms will be established as was found for the interaction of alkali cations with ether oxygens.[25] A comprehensive search for existing crystal structures to determine this point appears to be warranted.

Conclusion

This work reports the first crystal structure determination of a sodium and of a potassium enolate of a simple ketone. The aggregation states of these enolates are tetrameric and hexameric, respectively. The aggregates are not similar to the (acetylcyclopentadienyl)sodium enolate[26] or to the 15-crown-5 complex of the sodium enolate of ethyl acetoacetate.[27] However, the tetrameric aggregate of the sodium enolate exhibits similarities to the cubic, THF solvated lithium enolate of pinacolone previously reported.[3] Nonetheless, subtle differences between the tetrameric alkali metal enolates in Figure 4 and in ref 3 are observable, not the least of which is the chirality and spontaneous resolution of the complex in Figure 4.[28]

The possibility that the pinacolone-solvated Na$^+$pin$^-$ enolate in Figure 4 is an intermediate along the reaction pathway of the aldol reaction has not escaped our attention. Precisely such an intermediate was postulated in the lithium aldol reaction.[29] Triage of the chiral Na$^+$pin$^-$ aggregate and analysis of the aldol product derived therefrom may provide a useful method to investigate the mechanism of this reaction. Certain similarities exist between the lithium and potassium enolates depicted in Figures 1 and 6. It remains to be established if the conformational differences found in the crystalline aggregates also exist in solution. Future studies to determine these points are anticipated.

Experimental Section

Unsolvated Lithium Enolate of 3,3-Dimethyl-2-butanone (2). A solution of 2.02 g (20 mmol) of distilled diisopropylamine in 7 mL of pentane was placed in a 40 mL, thick-walled centrifuge tube along with a magnetic stir bar. The tube are flushed with N_2 and sealed with a serum stopper. To this solution, cooled to 0 °C in an ice bath, was added via syringe ≅ 8.3 mL of 2.4 m *n*-BuLi[30] (20 mmol) in hexane with vigorous stirring during 1 min. Toward the end of the addition the mixture became syrupy and stirring was no longer possible. The reaction mixture was placed in a freezer for several hours during which time a white precipitate of LDA formed. Excess solvent was removed via syringe and the precipitate washed with fresh pentane (3 × 6 mL) by introduction and removal of the solvent with a syringe.

Heptane (4–6 mL) was added to cover the amide base and the reaction mixture cooled to 0 °C in an ice bath. A solution of 1.90 g (19 mmol) of 3,3-dimethyl-2-butanone in heptane (8 mL) was added dropwise via syringe pump to the LDA suspension during 30 min. It is important that vigorous stirring be maintained during this addition to ensure complete reaction. After the addition is complete practically all of the LDA disappears although occasionally a trace of insoluble material is left. The reaction is placed in a freezer at −28 °C. Beautiful, clear prismatic crystals of lithium enolate grow over a period of 12 h.

Excess solvent is removed via syringe and quick evacuation of the reaction vessel removes the last traces of solvent. The average yield of enolate crystals from many different reactions is 1.0 g (9.3 mmol, 49%). A crystal (≅0.4 × 0.45 × 0.42 mm) was selected and rapidly mounted on the end of a glass fiber in a cold stream (≅ −100 °C) of dry N_2 on the diffractometer. Diffraction data were collected in two shells over a period of 60 h on two separate crystals in the range 3.5° ≤ θ ≤ 45°. The X-ray diffraction experiment is summarized in Table I and in the supplementary material.[15]

Upon warming to room temperature, the clear prismatic lithium enolate crystals gradually crumble to a fine powder. This powder appears to be stable for long periods when kept in a dry, oxygen-free environment. It is conveniently handled at room temperature for short periods, e.g., weighing on a balance, just as other (e.g., LAH) moisture-sensitive reagents. The powder was shown to be enolate by NMR spectroscopy: ^{1}H NMR ($CDCl_3$, 60 MHz) δ 1.12 (s, 9 H), 3.52 (s, 1 H), and 3.75 (s, 1 H).

Pinacolone-Solvated Sodium Enolate of 3,3-Dimethyl-2-butanone (3). A quantity of 3.67 g (20 mmol) of NaHMDS,[9] freshly crystallized from toluene, was placed in a small vial and covered with heptane (4–6 mL). This suspension was cooled to 0 °C and a solution of 1.90 g (19 mmol) of 3,3-dimethyl-2-butanone in heptane (7 mL) was added dropwise over a period of 30 min. Magnetic stirring was maintained throughout the

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[25] Chakrabarti, P.; Dunitz, J. D. *Helv. Chim. Acta* **1982**, *65*, 1482.

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[27] Cambillau, C.; Bram, G.; Corset, J.; Riche, C. *Can. J. Chem.* **1982**, *60*, 2554.

[28] No attempt was made to determine the absolute configuration of this aggregate.

[29] Seebach, D.; Amustutz, R.; Dunitz, J. D. *Helv. Chim. Acta* **1981**, *64*, 2622.

[30] *n*-BuLi was purchased from Alfa as a 2.4 M solution in hexane and used directly as purchased.

addition. The solution was placed in a freezer at −28 °C overnight during which time a few clear, prismatic crystals grew.

Excess solvent was removed via syringe. An appropriately sized crystal was selected and rapidly mounted on the end of a glass fiber in a cold stream ($\cong$ −100 °C) of dry N_2 on the diffractometer. Preliminary rotation photographs were followed by X-ray data collection in the range $3.5° \le \theta \le 45°$. The X-ray diffraction experiment is summarized in Table I and in the supplementary material.[15]

THF-Solvated Potassium Enolate of 3,3-Dimethyl-2-butanone (4). A quantity of 3.99 g (20 mmol) of crystalline potassium hexamethyldisilazane[10] was placed in a reaction vessel and covered with heptane (4–6 mL). This suspension was cooled to 0 °C and a solution of 1.90 g (19 mmol) of 3,3-dimethyl-2-butanone and 1.44 g (20 mmol) of THF in heptane (5 mL) was added dropwise over a period of 30 min. Magnetic stirring was maintained throughout the addition. When the addition was complete a small quantity of THF ($\cong$0.5 mL) was added to dissolve the remaining solids. The solution was placed in a freezer at −28 °C overnight during which time the enolate crystals formed. No yield was determined.

Excess solvent was removed with a syringe. A crystal was selected and mounted on the diffractometer as with the previous compound. The parameters of the X-ray diffraction experiment are summarized in Table I and in the supplementary material.[15]

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Registry No. 1, 99016-93-0; **2**, 99016-94-1; **3**, 99016-95-2; $t\text{-BuCOCH}_2^-\cdot\text{Li}^+$, 70367-67-8; $t\text{-BuCOCH}_2^-\cdot\text{Na}^+$, 99016-96-3; $t\text{-BuCOCH}_2^-\cdot\text{K}^+$, 55440-76-1; 3,3-dimethyl-2-butanone, 75-97-8.

Supplementary Material Available: Crystallographic details including anisotropic thermal parameters, bond lengths, and angles for compounds **3** and **4** (14 pages). Ordering information is given on any current masthead page.

Deuterium Kinetic Isotope Effects in the 1,4-Dimethylenecyclohexane Boat Cope Rearrangement

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Abstract: In order to examine the extent of bond making in the boat-like 3,3-sigmatropic shift transition states, *trans*-2,3-dimethyl-1,4-dimethylenecyclohexane (T) and its exomethylene tetradeuteria derivative (TXD) were prepared. The 3,3-shift of TXD at 305 °C results in interconversion of starting material, 5,5,6,6-tetradeuterio-*trans*-2,3-dimethyl-1,4-dimethylenecyclohexane (TND), and 2,2,3,3-tetradeuterio-*anti*-1,4-diethylidenecyclohexane (AD). A kinetic analysis of the first-order rate equations for the three-component system in both protio and deuterio species by numerical integration of the data and simplex minimization of the rate constants with symmetry and the assumption of no equilibrium or kinetic isotope effect on the TND-AD reaction gives a bond making kinetic isotope effect of 1/1.04 (0.04). The equilibrium isotope effects observed are 1/1.16 (0.04) so that the extent of bond formation in this boat-like bicyclo[2.2.2]octyl transition state is roughly 25%, a value to be compared with ca. 67% in chair-like acyclic 3,3-shift transition states. This rules out significant intervention of a bicyclo[2.2.2]octane-1,4-diyl intermediate or transition state.

Double allylic transposition of 1,5-hexadienes under thermal conditions is a subset in the category of 3,3-sigmatropic shifts. The general reaction type was discovered by Claisen with allyl vinyl ethers,[1] and Hurd first attempted to extend the reaction to dienes.[2] Cope provided numerous examples of the reaction in all carbon cases.[3] The reaction rate does not respond to changes in solvent polarity indicating a nonpolar mechanism. There is the strong suggestion that the reaction is concerted since the rate is far faster than what would be expected for cleavage to two allyl radicals; the pairwise interchange of C-1 and C-6 with C-3 and C-4 is also consistent with this hypothesis. There is evidence, from secondary deuterium kinetic isotope effects, that the transition-state structure, vis-à-vis the extent of C-3,C-4 bond breaking and C-1,C-6 bond making, is variable depending on the radical stabilizing ability and position of substituents.[4] Suggestions made by Dewar that a cyclohexane-1,4-diyl is an intermediate in the reaction[5] are not consistent with the isotope effects.

The Woodward–Hoffmann rules[6] suggest that there are four possible concerted transition states: chair, boat, twist, and plane. Recently Benner has shown that the latter two, which are antarafacial–antarafacial processes, may not be involved at temperatures below the cleavage temperature of 1,3,4,6-tetramethyl-1,5-hexadienes.[7] But the distinction between chair and boat was made much earlier by Doering and Roth, who examined the stereochemistry of the rearrangements of *threo-* and *meso*-3,4-dimethyl-1,5-hexadiene.[8] The boat pathway was ca. 6 kcal/mol higher in energy than the chair.

Goldstein examined the high-temperature rearrangement of a deuterated 1,5-hexadiene and also found evidence for a boat process 5.8 kcal/mol higher in energy.[9a] Further, he determined the activation enthalpy and entropy for the boat reaction to be

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[†] Taken wholey from the Ph.D. Thesis of J.L.J., Indiana University, December 1984.

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