TETRAHEDRAL CARBON AND INTERSTITIAL ELECTRONS IN Li CLUSTER: CL14 AND (LICH3)4(U) PENNSYLVANIA UNIV PHILADELPHIA DEPT OF PHYSICS R P MESSMER ET AL JAN 87 UNCLASSIFIED TR-4 N00014-86-K-0304
Tetrahedral Carbon and Interstitial Electrons in Li Cluster: CLi₄ and (LiCH₃)₄

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Tetrahedral Carbon and Interstitial Electrons in Li Clusters:

$\text{CLi}_4$ and $(\text{LiCH}_3)_4$

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The use of ab initio electronic structure calculations which include important electron correlation effects have yielded recently two quite significant findings. The first is the discovery by McAdon and Goddard\cite{1} that bonding in alkali metal clusters and simple metals is via interstitial one-electron bonds. The second is that the carbon atom employs essentially tetrahedral hybrid orbitals not only for single bonds in saturated molecules, but also for double bonds\cite{2,3}, triple bonds\cite{4,5} and conjugated molecules such as benzene\cite{6}. The object of the present work is to illustrate how these two concepts about chemical bonding can be combined to provide a simple consistent physical picture of the bonding in $\text{CLi}_4$ and $(\text{LiCH}_3)_4$. The basic principles illustrated by these two molecules provide the basis for understanding the structure and bonding of a wide class of organolithium compounds.

There is chemical evidence\cite{7} for the existence of $\text{CLi}_4$ but the molecular structure does not appear to have been determined. However, ab initio calculations using the molecular orbital approximation have calculated the most stable
structure to be tetrahedral in nature.\textsuperscript{9,10} On the basis of the results of previous
generalized valence bond calculations,\textsuperscript{1-7} one would anticipate the bonding in
\textit{CLi}_4 to be described in the following manner: (1) there will be four interstitial
electrons, one localized in each of the four faces of a tetrahedron of Li atoms, (2)
there will be a carbon atom at the center of the Li-tetrahedron which has four
tetrahedrally-oriented hybrid orbitals each containing one electron and each
pointing toward one of the faces of the tetrahedron, (3) an interstitial orbital and
a carbon hybrid orbital mutually overlap to form a two-electron bond in each of
the four tetrahedral faces. This description contrasts markedly with previous dis-
cussions of the bonding,\textsuperscript{8} yet it is the one we find via the generalized valence
bond (GVB) calculations\textsuperscript{11} described below.

The bonding in \textit{(LiCH}_3\textsubscript{4}) should be similar to that of \textit{CLi}_4 as far as the
tetrahedron of Li atoms is concerned, however the species bonding to the intersti-
tial electrons is no longer a single carbon atom forming four bonds from the inte-
rior of the Li cluster, but four methyl radicals bonding to the faces from the exte-
rior of the cluster. Again, this simple physical picture is verified by the calcula-
tions presented below.

In Figure 1a, the geometry of the \textit{CLi}_4 molecule is illustrated and a schematic
representation of the orbitals describing one of the carbon-metal bonds is shown.
Figure 1b shows a contour plot of one of the four equivalent bonding orbitals, \(\psi_{\text{cl}}\), in the tetrahedral \textit{Li}_4 cluster.\textsuperscript{12} The electron described by this orbital is
localized in the face containing Li atoms 1, 3 and 4. The orbital contour plots of
Fig. 1c show the two orbitals of the bond in the face of the Li cluster, while Fig.
1d shows the same two orbitals in the plane containing Li atoms 1 and 2 and the
carbon atom. The left panel of Fig. 1d should be compared to Fig. 1b — it shows
the effect of the carbon atom on an interstitial electron in a face of the Li cluster.
Because of its less screened nuclear charge, the carbon atom localizes the orbitals
in the Li cluster faces to a greater extent than they are in the isolated metal cluster. This also facilitates better bonding between the metal and carbon. There are four equivalent bonds in $\text{CLi}_4$, only one of which is illustrated in Figure 1.

The bonding in the $(\text{LiCH}_3)_4$ molecule can be understood by removing the interior carbon atom of Figure 1 and replacing it with four external methyl groups. The structure is shown schematically in Figure 2a where one set of the only unique types of bonds (C-H and C-Li cluster bonds) are highlighted. The contour plots in Figs. 2b and 2c are in the plane of the atoms $\text{H}_1$, $\text{C}_1$, $\text{Li}_1$ and $\text{Li}_2$ shown in Fig. 2a. In the contour plots of Fig. 2b, one can observe how orbital $\phi_{1s}'$ of the Li$_4$ cluster is modified by bonding to the free orbital of a methyl radical ($\phi_{1s}$). A C-H bond is illustrated by the contour plots of Fig. 2c; note the similarity of the $\text{C}_1$ orbitals $\phi_{1s}$ and $\phi_{2s}$, one of which is bonded to the face of the Li cluster while the other is bonded to a hydrogen atom. The geometry for our calculations was taken from the solid state structure, and a double zeta basis set was used in the calculations.

Previous calculations on $(\text{LiCH}_3)_4$, using localized molecular orbitals to discuss the bonding, have described the bonding as highly ionic in character and showing "essentially no metal-metal bonding". These descriptions contrast markedly with that obtained above. Furthermore, the differences between molecules containing carbon and hydrogen and those containing carbon and lithium is quite apparent and not very surprising. This contrasts with the view: "Surprisingly, when lithium is involved instead of hydrogen, the situation is completely different." In fact, the bonding picture which emerges from our work is close to the qualitative discussion given by Stucky and coworkers.

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[10] We adopt the calculated geometry of Ref. 8 as an expedient rather than calculating the optimal geometry using our correlated wave functions. Our interest here is in understanding the nature of the bonding rather than in determining accurate geometrical parameters for the molecule.

[12] The calculations for the Li$_4$ cluster are for the quintet state as it is the most appropriate reference for discussing the two molecules considered here. Note that unlike covalently bonded systems, the high spin state of Li$_4$ is also bound. See ref. [1].


[17] The ease with which Li forms hybrids from its s and p orbitals leads to properties vastly different from those of H. See refs. [1], [18] and [6].


Figure Captions

Figure 1

(a) Schematic representation of the $\text{C}_{\text{Li}_4}$ structure showing one of the four equivalent bonds. $\phi_{1a}$ is an interstitial electron in a face of the $\text{Li}_4$ tetrahedron; $\phi_{2a}$ is a hybrid orbital on carbon pointing into a face of the tetrahedron. These two orbitals overlap to form one of the four bonds.

(b) Contour plot of one of the interstitial orbitals ($\phi_{1a}'$) of the $\text{Li}_4$ tetrahedron before the carbon atom is introduced.

(c) Contour plots of the two orbitals of (a), which form one of the carbon-metal bonds. Plots are in a triangular face of the $\text{Li}_4$ tetrahedron.

(d) Contour plots of the same two orbitals, but in the plane used in (b). The contours used in this Figure and in Figure 2 have the most diffuse contour as 0.025 au and the contours increment in steps of 0.025 au.

Figure 2

(a) Schematic representation of the $\text{LiCH}_3$ tetramer structure showing an example of the two types of bonds formed. $\phi_{1a}'$ and $\phi_{2a}'$ form a carbon-metal bond, while $\phi_{2a}$ and $\phi_{2a}$ form a carbon-hydrogen bond. The symbol "Me" shows the positions of the other methyl groups.

(b) Contour plots of the orbitals forming the carbon-metal bond in the plane containing atoms $\text{H}_1$, $\text{C}_1$, $\text{Li}_1$, and $\text{Li}_2$.

(c) Contour plots of the orbitals forming a carbon-hydrogen bond in the same plane as in (b).
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