

Inorganic Chemistry with Ylides

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Modern nomenclature uses the term "ylide" for a class of compounds which was first considered by Staudinger¹ in the 1920's and was later developed by Wittig² and his collaborators after World War II. The most important representatives of this class are the phosphorus ylides, bonding in which is depicted:²



According to this representation, two canonical formulas are of principal significance for proper description of the structure and bonding. One of these, the *ylide formula* in the narrow sense, emphasizes the dipolar zwitterionic nature involving an *onium center* at elements like phosphorus, sulfur, nitrogen, or arsenic, next to a *carbanionic function*, which may be at least partially delocalized into suitable substituents. In the *ylene formula*, on the other hand, a true double bond is postulated between the onium center and the ylidic carbon, thus reducing or even eliminating the formal charges at these atoms.^{3,4}

The application of modern physical techniques⁵ and the results of sophisticated theoretical calculations⁶⁻⁸ have made it increasingly clear that the ylide formula predominates in the ground states of these and related molecules. Most of the early investigators successfully used this description for most of their problems of structure and reactivity and for the rationalization of reaction mechanisms.²⁻⁴ Therefore it is with justification that the term "ylide" is used nowadays almost exclusively in the literature.

When working with ylides we are, therefore, dealing with stable compounds containing a special type of carbanion! These carbanions are not associated with metallic cations, as in many organometallic reagents, but with an onium group fixed in a certain position of the system and giving rise to new specific features.

It is only 20 years since ylides, predominantly those of phosphorus and sulfur, were introduced as reagents into organic synthesis. Today they rank among the most important tools of the preparative organic chemist both in research and in industry, as, e.g., in the Wittig olefin synthesis.

Until recently, however, inorganic and organometallic chemists seem to have neglected the great po-

tential of ylides. To judge from the literature, there was no more than preliminary study of the role of ylides in reactions with inorganic components before 1965. Various groups have since been attracted more and more by the many fascinating aspects of this new branch of organometallic chemistry.

Starting from simple silicon and other main-group derivatives of ylides, this chemistry has now expanded to transition metals as possible coordination centers for ylidic carbanions. Ylides are considered as versatile ligands to metals in their various oxidation states. Ylide chemistry with silicon was first applied to organic and organometallic synthesis, and the latter aspect has been found promising in the field of transition-metal catalysis.

Silicon in Ylide Chemistry

In view of the many successful applications of ylides in organic chemistry, it must have appeared logical to extend this chemistry to silicon, the homolog of carbon. Experienced organometallic chemists made this first important step and discovered the high affinity of ylidic carbanions toward silicon,⁹⁻¹³ germanium,¹³ and tin.^{9,12,13} It soon appeared, however, that silicon exerted a pronounced stabilizing effect on these carbanions^{13,14} which was contrary to all expectations based on electronegativity arguments and the relative inductive effects of alkyl and silyl groups.

This phenomenon is particularly obvious from a comparison of the structures of some corresponding alkylated and silylated ylides¹⁵ (Scheme I). The deprotonation of phosphonium and sulfoxonium^{16,17} cations by organometallic bases occurs selectively at the least alkylated α -carbon atom, (1 \rightarrow 2, 3 \rightarrow 4). On the other hand, silylated onium cations are converted into ylides having the silicon substituent di-

(1) H. Staudinger and J. Meyer, *Helv. Chim. Acta*, **2**, 635 (1919).

(2) G. Wittig and G. Geissler, *Justus Liebig's Ann. Chem.*, **580**, 44 (1953); G. Wittig and U. Schöllkopf, *Chem. Ber.*, **87**, 1318 (1954).

(3) A. W. Johnson, "Ylid Chemistry," Academic Press, New York, N.Y., 1966.

(4) G. M. Kosolapoff and L. Maier, Ed., "Organophosphorus Chemistry," Wiley, New York, N.Y., 1972.

(5) See the section salt-free ylides below.

(6) R. Hoffmann, D. B. Boyd, and S. Z. Goldberg, *J. Amer. Chem. Soc.*, **92**, 3929 (1970).

(7) J. Absar and J. R. Van Wazer, *J. Amer. Chem. Soc.*, **94**, 2382 (1972).

(8) D. B. Boyd and R. Hoffmann, *J. Amer. Chem. Soc.*, **93**, 1063 (1971).

(9) D. Seyferth and S. O. Grim, *Chem. Ind. (London)*, 849 (1959); *J. Amer. Chem. Soc.*, **83**, 1610 (1961); **83**, 1613 (1961).

(10) H. Gilman and R. A. Tomasi, *J. Org. Chem.*, **27**, 3647 (1962).

(11) D. Seyferth and G. Singh, *J. Amer. Chem. Soc.*, **87**, 4156 (1965).

(12) D. Seyferth, G. Singh, and R. Suzuki, *Pure Appl. Chem.*, **13**, 1596 (1966).

(13) N. E. Miller, *J. Amer. Chem. Soc.*, **87**, 390 (1965); *Inorg. Chem.*, **4**, 1458 (1965).

(14) H. Schmidbaur and W. Tronich, *Chem. Ber.*, **100**, 1032 (1968).

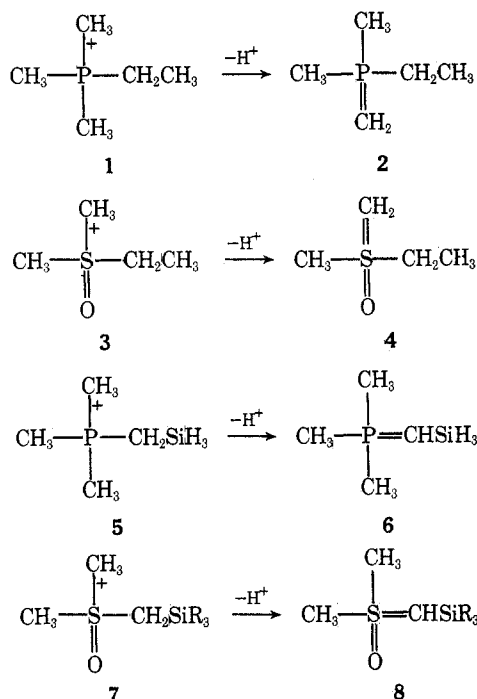
(15) H. Schmidbaur and W. Malisch, *Chem. Ber.*, **103**, 3007 (1970).

(16) H. Schmidbaur and G. Kammel, *Chem. Ber.*, **104**, 3252 (1971).

(17) H. Schmidbaur and W. Kapp, *Chem. Ber.*, **105**, 1203 (1972).

Hubert Schmidbaur was born at Landsberg am Lech, Bavaria, in 1934. He studied at the University of Munich, where he obtained the Dr. rer. nat. degree under Max Schmidt. He served as assistant and lecturer at Munich and then at Marburg, as Professor of Inorganic Chemistry at the University of Würzburg (1967-1973), and is now Professor of Inorganic and Analytical Chemistry at the Technical University of Munich. He was recipient of the Dozentenpreis des Verbands der Chemischen Industrie in 1966 and of the 1974 Frederic Stanley Kipping Award in Organosilicon Chemistry sponsored by Dow Corning Corporation.

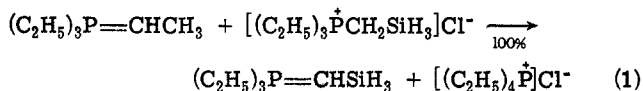
Scheme I



rectly attached to the carbanion generated in the process (5 → 6, 7 → 8), even if alternatives are available. This phenomenon does not have its origin in a steric effect, since simple SiH₃ substituents¹⁵ behave the same as bulky SiR₃ groups.^{13,14}

Essentially the same behavior is encountered with arsenic ylides^{13,18} and with various organosilicon, -germanium,¹⁴ -tin,¹⁴ -phosphino,^{19,20} -arsino,¹⁹ -stibino,¹⁹ and -phosphonium or -arsonium^{19,21} substituents at the ylidic carbon.

Among the most striking consequences of the "silicon effect" in ylides is the course of some transylidation^{15,22} reactions. Transylidation²³ occurs between ylides and onium salts when the competing ylides differ significantly in basicity or when there are large differences in lattice energies of the onium salts. Equation 1 gives an example which demonstrates the reduced basicity of an ylide bearing a silicon substituent as compared to the alkylated analog. (The lattice energies of the salts in this particular case should be very similar.)

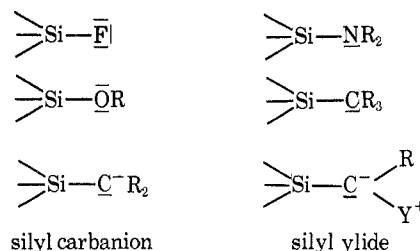


The stabilizing effect of main-group elements like silicon in ylides and the related reduction of ylide basicity have been interpreted in terms of a d-orbital participation in the Si-carbanion bonding^{13,14} and on simple electrostatic grounds.¹⁵ The latter concept emphasizes the increase in space around the carban-

ionic center and the corresponding reduction of repulsive forces between the high electron density of the ylidic carbon and the bonding electrons of the σ framework upon introduction of the larger third-row elements.

Though neither of these pictures is very satisfactory, it is gratifying that such recent physical data as ¹³C resonance studies²⁴ and photoelectron work²⁵ fully support the more qualitative findings from synthesis and chemical reactions.

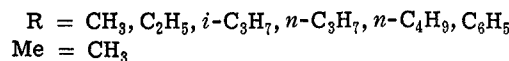
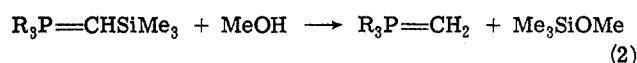
Most of the questions about the bonding of silicon in ylides concern the general problem of interactions between this element and atoms like fluorine, oxygen, and nitrogen, which are known to form exceedingly strong bonds to silicon.²⁶ All of these have at least one lone pair of electrons.



The Role of Silyl Ylides in Synthesis

Shortly after their first preparation, silylated ylides were found to be very useful in synthesis. In fact it appeared that some very important basic members of the ylide series were initially accessible only *via* their silyl derivatives.^{18,27}

Salt-free trialkylphosphonium alkylides were obtained for the first time in a pure state through a *desilylation* process using alcohols or silanols²⁷ (eq 2). (Since then, the more traditional methods of syn-



thesis have been developed further and, with some modifications, are now also applicable²⁸.) The same was true for the initial synthesis of trimethylarsenic methyllide, (CH₃)₃AsCH₂, which was obtained through desilylation of a silylated precursor.¹⁸ Dimethylsulfoxonium methyllide, (CH₃)₂S(O)CH₂, is accessible *via* various routes, one of which is again a desilylation process.²⁹

The silylated precursors, representing the starting materials for eq 2, are now readily available with a large variety of substituents.^{14,15,22,26,27,30,31} Besides trialkylsilyl groups, a number of di-, tri-, and even tetrafunctional silyl components have been used as ligands to the ylidic carbanions attached to phosphorus and sulfur. These lead to new types of

(18) H. Schmidbaur and W. Tronich, *Inorg. Chem.*, **7**, 168 (1968).

(19) H. Schmidbaur and W. Tronich, *Chem. Ber.*, **101**, 3545 (1968).

(20) H. Schmidbaur and W. Malisch, *Chem. Ber.*, **104**, 150 (1971). *Angew. Chem.*, **82**, 84 (1970); *Angew. Chem., Int. Ed. Engl.*, **9**, 77 (1970).

(21) G. H. Birrum and C. N. Matthews, *J. Amer. Chem. Soc.* **88**, 4198 (1966).

(22) H. Schmidbaur, H. Stühler, and W. Vornberger, *Chem. Ber.*, **105**, 1084 (1972).

(23) H. J. Bestmann, "Neuere Methoden präp. org. Chem.," Vol. V, Verlag Chemie, Weinheim/Berstr., 1967.

(24) H. Schmidbaur and F. H. Kohler, unpublished results.

(25) K. A. Ostoja-Starzewski, H. tom Dieck, and H. Bock, *J. Organometal. Chem.*, **65**, 311 (1974).

(26) H. Schmidbaur, *Advan. Organometal. Chem.*, **9**, 260 (1970).

(27) H. Schmidbaur and W. Tronich, *Angew. Chem.*, **79**, 412 (1967); *Angew. Chem., Int. Ed. Engl.*, **6**, 448 (1967); *Chem. Ber.*, **101**, 595 (1967).

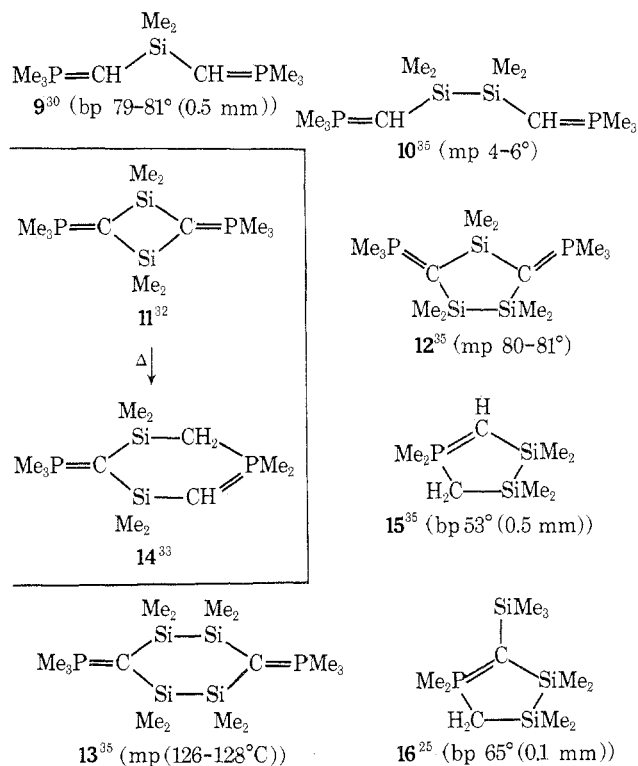
(28) R. Köster, D. Simić, and M. A. Grassberger, *Justus Liebigs Ann. Chem.*, **739**, 211 (1970).

(29) H. Schmidbaur and W. Tronich, *Tetrahedron Lett.*, 5335 (1968).

(30) H. Schmidbaur and W. Malisch, *Chem. Ber.*, **102**, 83 (1969).

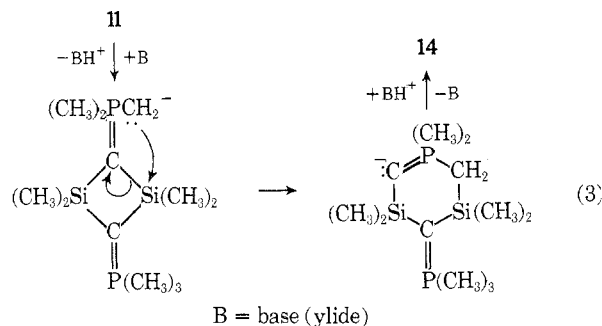
(31) H. Schmidbaur and W. Malisch, *Chem. Ber.*, **103**, 3448 (1970).

difunctional open-chain and cyclic ylides, as indicated by examples 9–16. Among these compounds the



bis(phosphoranylidene)disilacyclobutanes of type 11 are of special interest.³² Here two carbanions are members of a small strained ring system, but obviously the presence of the two silicon atoms provides stabilization to the system.²⁵ The carbon analogs have never been observed.

At elevated temperature and in the presence of excess ylide as a catalyst, the four-membered ring undergoes an isomerization through ring expansion³³ (11 → 14). The mechanism of this catalysis involves the excess ylide simply as a deprotonating and reprotonating agent (eq 3). The consequence of this new

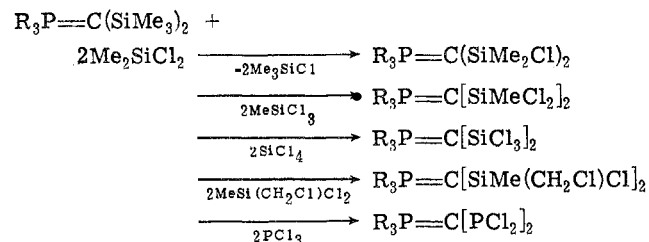


type of carbanionic rearrangement involving silicon³⁴ is to provide an even better separation of the two centers of negative charge.

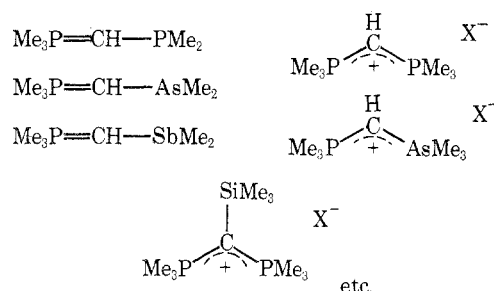
The disilanyl species 10, 12, 13, 15, and 16^{35,36} were investigated to obtain information on possible

delocalization of the carbanionic charge into the Si-Si moieties, a potential (p → d → d) system, but no direct evidence was found.^{36,25}

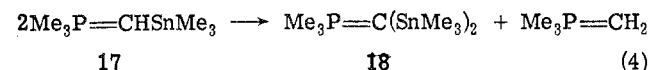
A broad variety of compounds was obtained through the new process of *transsilylation*.²⁰ This method provides a means of introducing more complicated substituents, starting from the simple trimethylsilyl ylides:



The last example²⁰ shows that other elements can, like phosphorus, be easily attached to the ylides by this technique. All of these are high-yield reactions, and the sole by-product is the volatile trimethylchlorosilane. Other phosphorus-, arsenic- and antimony-substituted ylides available^{14,21,37} are of the following types.



In this connection it should be pointed out that the *heavy* group IV and V elements are found to occur almost exclusively as disubstituted ylides. Thus, whereas a species of formula 18 is easily prepared, the corresponding compound 17 could not be isolated¹⁴ (eq 4). It is probably not simply a coinci-



dence that similar findings have been reported for stannyldiazoalkanes:³⁸ $[N \equiv N^+ - C^-] [Sn(CH_3)_3]_2$. Further work on this problem is desirable.

Desilylation-Generated Salt-Free Ylides

The isolation of salt-free high-purity ylides through desilylation (eq 2) provided an excellent basis for a new systematic investigation of the properties of these fascinating compounds. For example, $(CH_3)_3P=CH_2$, shortly after its preparation as a salt-free substance, was subjected to detailed ¹H, ¹³C, and ³¹P nmr,^{39–41} infrared and Raman,⁴² dipole

(37) K. Issleib and R. Lindner, *Justus Liebig's Ann. Chem.*, 699, 40 (1966).

(38) M. F. Lappert, J. Lorberth, and J. S. Poland, *J. Chem. Soc. A*, 2954 (1970).

(39) H. Schmidbaur and W. Tronich, *Chem. Ber.*, 101, 604 (1968).

(40) H. Schmidbaur, W. Buchner, and D. Scheutzw, *Chem. Ber.*, 106, 1251 (1973).

(41) K. Hildenbrand and H. Dreeskamp, *Z. Naturforsch. B*, 28, 226 (1973).

(42) W. Sawodny, *Z. Anorg. Allg. Chem.*, 368, 284 (1969).

(32) H. Schmidbaur and W. Malisch, *Chem. Ber.*, 103, 97 (1970).

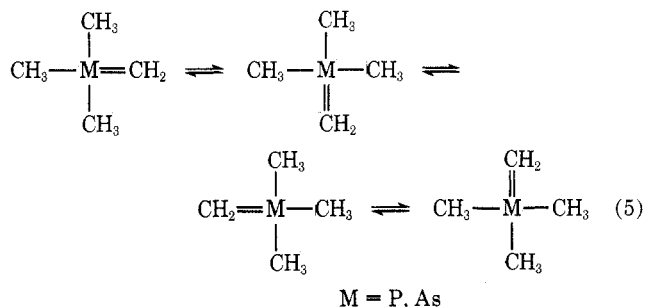
(33) W. Malisch and H. Schmidbaur, *Angew. Chem.*, 86, 554 (1974).

(34) R. West, R. Lowe, H. F. Stewart, and A. Wright, *J. Amer. Chem. Soc.*, 93, 282 (1971), and earlier papers.

(35) H. Schmidbaur and W. Vornberger, *Angew. Chem.*, 82, 773 (1970); *Angew. Chem., Int. Ed. Engl.*, 9, 737 (1970).

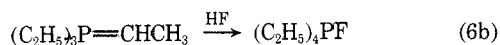
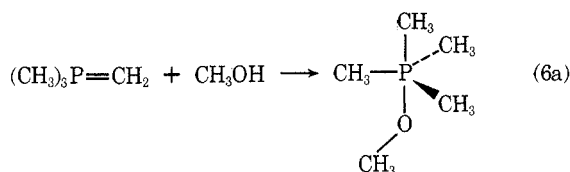
(36) H. Schmidbaur and W. Vornberger, *Chem. Ber.*, 105, 3173 (1972); 105, 3187 (1972).

moment,⁴³ and photoelectron studies.^{25,44} From this careful work a better insight into the nature of bonding,²⁵ and also into the features of the rapid inter- and (possibly) intramolecular proton exchange, was obtained. Although much information has been accumulated to date, no specific mechanism for this prototropy has been established, nor has a solution been found by theoretical calculations.^{6,8}



Tetraalkylalkoxyphosphoranes and -fluorophosphoranes

The desilylation-generated salt-free ylides gave access, for the first time, to tetraalkylalkoxyphosphoranes and related compounds, through carefully controlled addition of alcohols, hydrogen fluoride,

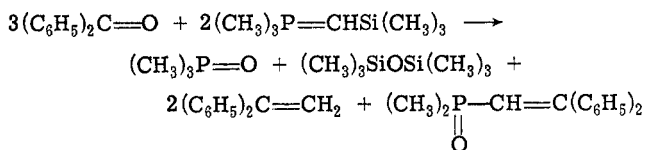


etc.⁴⁵⁻⁴⁸ Some of these molecules were easily characterized as containing pentacoordinate phosphorus atoms.⁴⁷ At low temperatures they are rigid on the nmr time scale and axial and equatorial alkyl groups can be clearly distinguished by ¹H and ¹³C techniques.^{47,49} This is the first case in which a direct comparison of axial and equatorial P-CH₃ bonding was possible. Excess alcohol converts R₄POR' compounds into phosphonium salts of hydrogen-bonded dropolyalkoxide anions of types R₄P⁺H-(OR')₂.^{47,50}

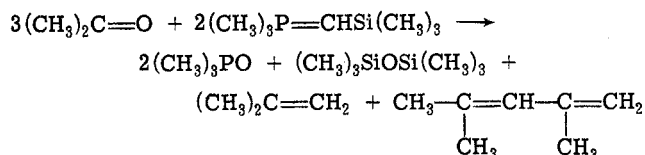
Silylated ylides react similarly with organic carbonyl compounds rather than paralleling the classic Wittig olefination process, because of a successful competition of silicon with phosphorus for the carbonyl oxygen atoms. Some typical examples have been described and can be explained on this basis.^{10,51} The underlying principle is therefore the

same as in the desilylation reactions with alcohols (see examples 1 and 2).

Example 1

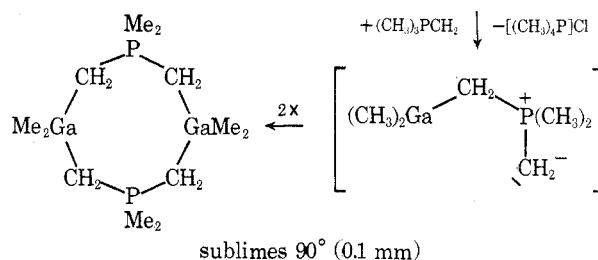
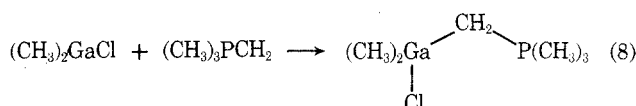


Example 2



Ylide Derivatives of Other Main-Group Elements

Apart from the homologs of silicon and phosphorus, some of the *group III and group II metals* appear to be suitable partners for reactions with ylides. Whereas with boron compounds only straightforward addition reactions had been observed in previous work,⁵²⁻⁵⁴ there is now evidence for a much more complicated system with the compounds of aluminum, gallium, indium, and thallium. In addition to simple 1:1 adducts of the classical type,²⁷ a new variation of the transylation process is observed⁵⁵ (eq 8) in secondary reactions. In this case, unlike the



behavior of the silylated phosphonium salts (eq 1), the deprotonation occurs at one of the alkyl groups attached to phosphorus, followed by ring closure through intercomplexation. Thus, the ylidic function is shifted away from the initial metal substituent.

The resulting heterocyclic species have alternating onium and metalate centers bridged by alkylene groups. In this structure, which is also widespread in transition-metal chemistry (see below), all the carbanionic centers can be accommodated at the acceptor sites of the metals, a feature masking the inherent ylidic character of the species and converting them into a special type of organometallic com-

(43) H. Schmidbaur, unpublished experiments.

(44) ESR studies have been carried out on arylated ylide radicals.

(45) H. Schmidbaur and H. Stühler, *Angew. Chem.*, **84**, 166 (1972); *Angew. Chem., Int. Ed. Engl.*, **11**, 145 (1972).

(46) H. Schmidbaur, K. H. Mitschke, and J. Weidlein, *Angew. Chem.*, **84**, 165 (1972); *Angew. Chem., Int. Ed. Engl.*, **11**, 144 (1972).

(47) H. Schmidbaur, H. Stühler, and W. Buchner, *Chem. Ber.*, **106**, 1238 (1973).

(48) H. Schmidbaur, K. H. Mitschke, W. Buchner, H. Stühler, and J. Weidlein, *Chem. Ber.*, **106**, 1226 (1973).

(49) H. Schmidbaur, W. Buchner, and F. H. Köhler, *J. Amer. Chem. Soc.*, **96**, 6208 (1974).

(50) H. Schmidbaur and H. Stühler, *Chem. Ber.*, **107**, 1420 (1974).

(51) H. Schmidbaur and H. Stühler, *Angew. Chem.*, **85**, 344 (1973); *Angew. Chem., Int. Ed. Engl.*, **12**, 320 (1970).

(52) M. F. Hawthorne, *J. Amer. Chem. Soc.*, **80**, 3480 (1958); **83**, 367 (1961).

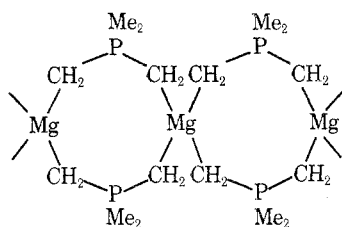
(53) D. Seyferth and S. O. Grim, *J. Amer. Chem. Soc.*, **83**, 1613 (1961).

(54) D. Seyferth, S. O. Grim, and T. O. Read, *J. Amer. Chem. Soc.*, **82**, 1510 (1960).

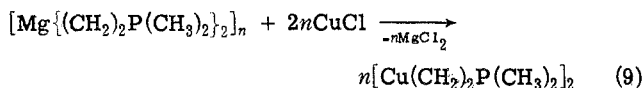
(55) H. Schmidbaur and H. J. Fuller, *Chem. Ber.*, **107**, 3674 (1974).

pound. The lack of a suitable acceptor site at the group IV elements obviously makes a similar reaction pathway unfavorable, and generation of a free ylidic function is the sole alternative.

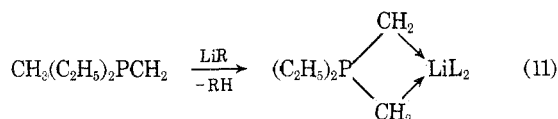
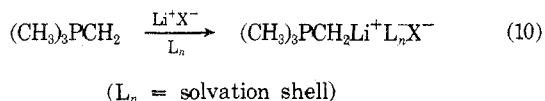
Magnesium alkyls have also recently been found to undergo reactions of this type with phosphorus ylides.⁵⁶ With these reagents the even higher acceptor capacity of the metal leads to the formation of a novel organomagnesium polymer:



The products of this reaction are themselves extremely reactive, and their chemistry is currently under more extensive investigation. Reactions with transition metal halides lead to ylide derivatives of these elements, as illustrated in eq. 9. The products of this type are discussed below.



The alkali metals have, for a long time, been known to form addition compounds with ylides;^{1,3,4} indeed the stability of some of these adducts is a major problem in the synthesis of "salt-free" ylides.^{3,4} Lithium salts in particular are strongly bonded to the ylidic carbanions, but little has been reported on the nature of these adducts⁵⁷ (eq 10). An nmr study of lithiated ylides⁵⁸ has, however, shown that metalation again occurs in the side chains and that there is equivalence of the two carbanionic centers in solution (see eq. 11). From studies of the ¹H-



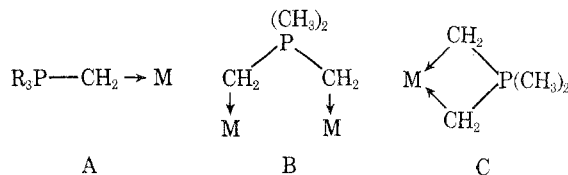
¹³C and ¹H-³¹P couplings a direct covalent interaction between the metal and the carbon atoms⁵⁸ was deduced. The state of oligomerization is unknown.

Ylide complexes of the salts of the heavier alkali metals are of much lower thermal stability, and the metalation products with these metals are very salt-like in character. A cesium derivative probably contains true (CH₃)₂P(CH₂)₂⁻ anions in a lattice with Cs⁺ cations.⁵⁹

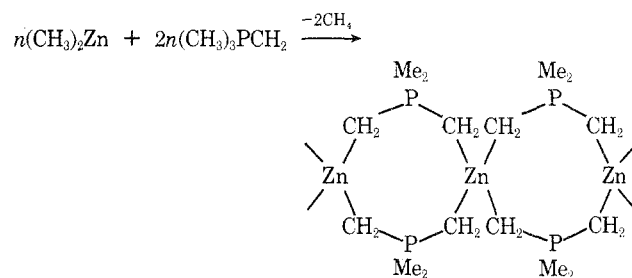
Transition Metal Chemistry of Ylides

Though a confusing variety of different types of products was initially obtained from reactions of yl-

ides with transition-metal derivatives, a general scheme which allows their classification is now slowly appearing. Again, the ylides may occur as simple terminal ligands (as in A), as bridging groups (as in B), or as chelating moieties (as in C). Both A and B had been previously found with main-group elements, but C is a new configuration.

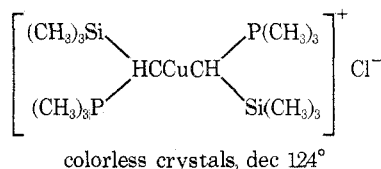
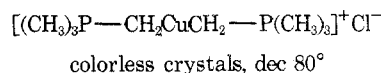


The most remarkable feature of transition-metal ylide chemistry is, however, the unusual thermal stability of the underlying organometallic bonds, M-C-P⁺, -S⁺, etc. This is not particularly striking with the new ylide derivatives of the d¹⁰ metal ions of zinc, cadmium,^{56,60} and mercury^{9,61-63} because the organometallic compounds of these elements are generally very stable anyway. Indeed, the high tendency toward formation and the stability of the Zn and Cd ylides merely reflects these characteristics. The general scheme for their formation parallels that of the magnesium species, and it is assumed that the principal products involve the B-type structure.



With mercury, simple addition to give A-type products is observed in most cases,^{61,62}

The inherent instability generally associated with *coinage metal* organometallics is, however, not reflected by the properties of the ylide complexes of copper, silver, and gold.⁶³⁻⁶⁵ Copper(I) halides and their phosphine complexes were shown⁶⁴ to form 1:2 coordination compounds containing two Cu-C bonds, which are thermally stable well above room temperature, *e.g.*



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(61) H. Schmidbaur and K. H. R athlein, *Chem. Ber.*, 106, 102 (1973).

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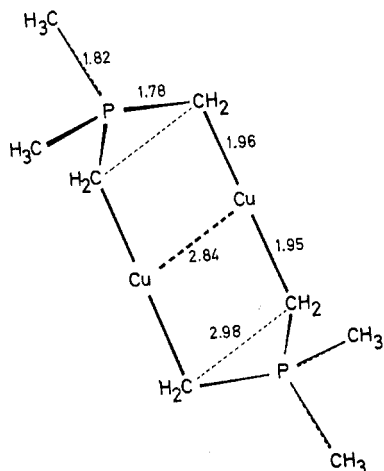
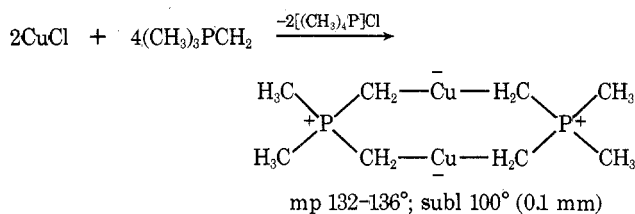


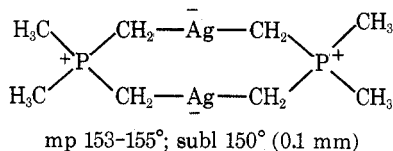
Figure 1.

Even molecular species, such as the ylide complex of trimethylsilylmethylcopper(I), are easily prepared and may be kept at 20° either as a solid or in solution: $(\text{CH}_3)_3\text{SiCH}_2\text{CuCH}_2\text{P}(\text{CH}_3)_3$, dec 30°. The structures of these compounds are illuminated by analytical and spectroscopic data, and a linear arrangement of the two Cu-C bonds was proposed. This proposal has now been confirmed in an X-ray analysis of the secondary product of the reaction of CuCl with excess $(\text{CH}_3)_3\text{PCH}_2$. Transylidation is again observed,⁶⁴ leading to a cyclic dimer:



The two C-Cu-C linkages of this eight membered heterocycle are linear and parallel to each other, and the ylidic bridges are in the form of strictly tetrahedral PC_4 moieties⁶⁶ (see Figure 1). The thermal stability of this compound is sufficient to permit sublimation at temperatures around 120° with only slight decomposition, and the molecular ion is observed.⁶⁴

A similar compound is also obtained with silver chloride.⁶⁴ For this species ^1H and ^{31}P nmr are of special interest, because the $^1\text{H-C}$ ^{107,109}Ag and $^{31}\text{P-C}$ ^{107,109}Ag couplings can be observed directly, providing evidence for the presence of covalent Ag-C



bonds. Similar compounds have been obtained from $\text{CH}_3(\text{C}_6\text{H}_5)_2\text{PCH}_2$ and $\text{C}_6\text{H}_5(\text{CH}_3)_2\text{PCH}_2$.⁶⁷

Gold is found to form an even wider range of exceedingly stable ylide compounds, and with this element the +3 oxidation state is also found in novel

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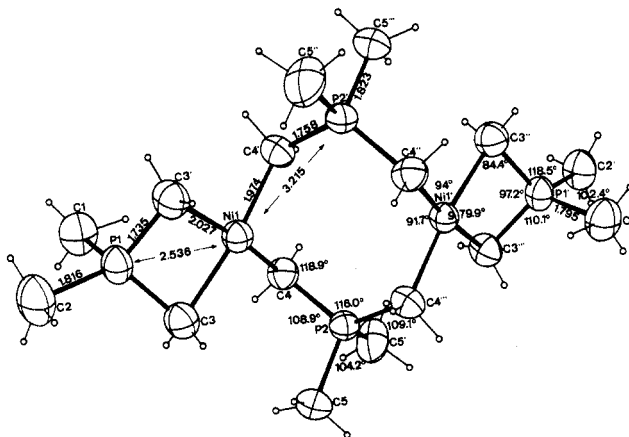


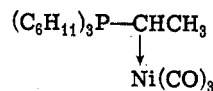
Figure 2.

metal ylides of square-planar d^8 configurations. In Scheme II appear several examples and the simple relations between some of them.^{65,68}

From divalent nickel a whole series of stable organometallic compounds has been detected through the reaction of various nickel alkyl and nickel halide complexes with ylides.⁶⁹ These range from simple dimethylnickel monomers⁷⁰ to bridged and cage-type molecules, in which the ylides sometimes occur as the only ligands to the metal⁷¹ (Scheme III).

The products of the reaction of $[(\text{CH}_3)_3\text{P}]_3\text{NiCl}_2$ with $(\text{CH}_3)_3\text{PCH}_2$ are particularly interesting because, depending on the conditions of crystallization or sublimation, several isomers may be obtained.⁷¹ The gas phase contains monomers or dimers, whereas two different dimers were observed (and isolated) from solution. One of the isomers (20) was subjected to a crystal structure determination and its constitution fully established⁷² (see Figure 2). This isomer contains the ylidic ligands $(\text{CH}_3)_2\text{P}(\text{CH}_2)_2^-$ both in the bridging position (B) and in the chelating position (C). It is, therefore, a very important example for illustrating the variety of ways in which ylides can interact with metals.

Zerovalent nickel had been previously shown^{73,74} to accommodate ylide molecules in its coordination sphere, but to date only the terminal (monodentate) mode of interaction (A) has been confirmed. A crystal structure⁷⁵ has been reported for a compound in the carbonyl series, and the spectra of these complexes have been carefully studied.⁷⁴



The reactions of palladium and platinum complexes with $(\text{CH}_3)_3\text{PCH}_2$ have yielded only salt-like

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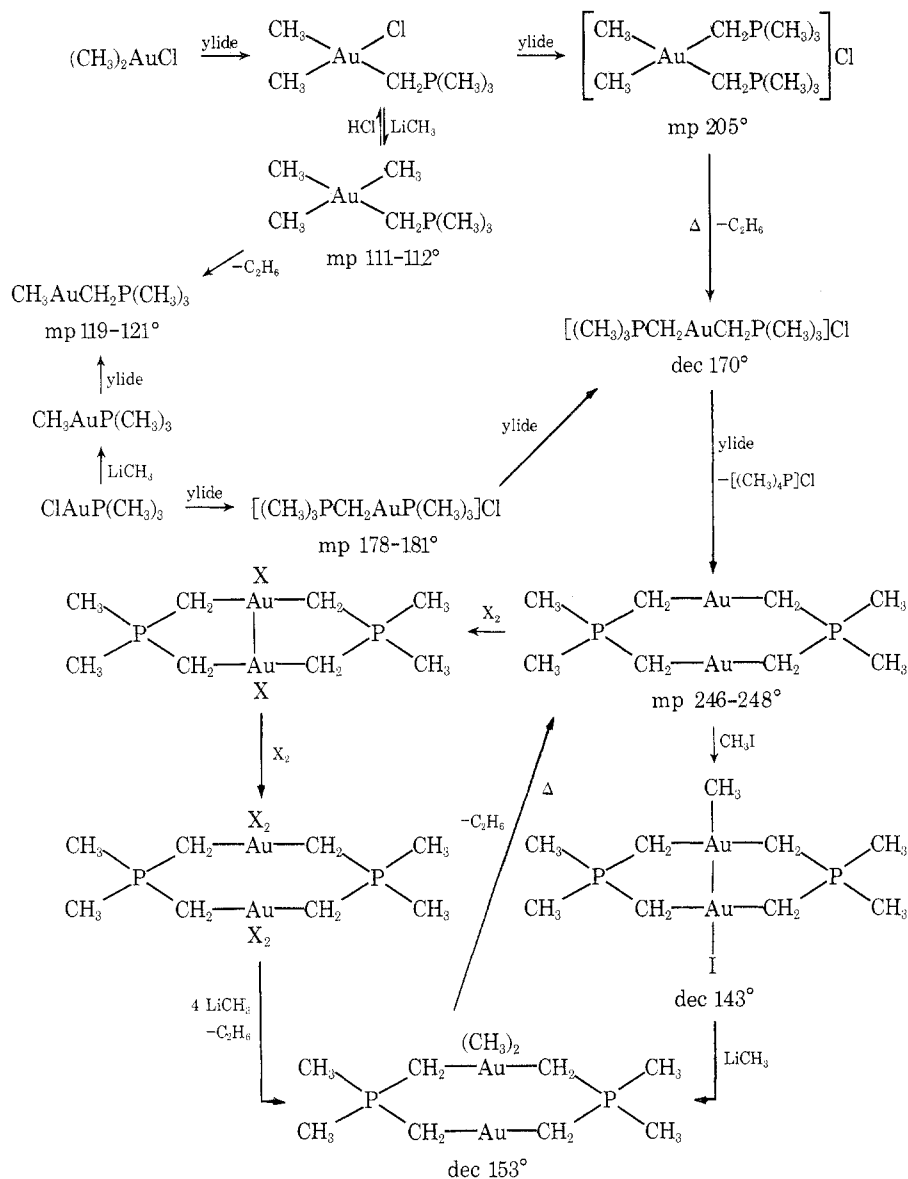
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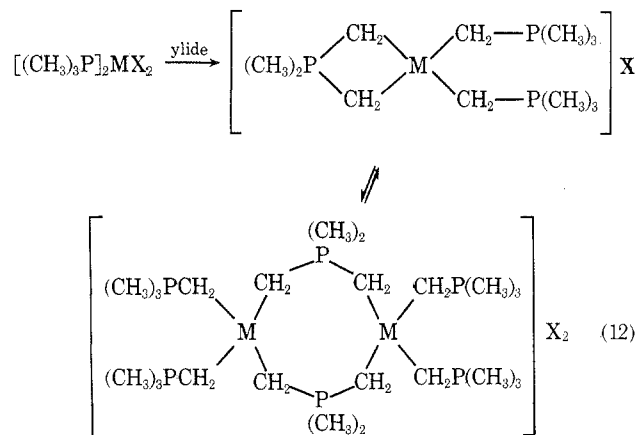
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Scheme II^a

^a Ylide = $(\text{CH}_3)_3\text{PCH}_2$, X = halogen.

products,⁷⁶ in which two different modes of interaction of ylidic carbanions with the metals are encountered. Though here the ylides fully occupy the first coordination sphere of the metals, there is only partial transylidation by excess ylide. Two of the ligands are left as monodentate groups, and one is converted into a bidentate moiety. The products are stable to air and moisture and have comparatively high decomposition temperatures (eq 12). In all of these compounds the metal atoms are again found to form no less than four stable σ bonds to carbon.

Recent work has also demonstrated that palladium can function as a coordination center for weakly basic⁷⁷ or unstable ylides⁷⁸⁻⁸⁰ of sulfur and nitrogen.



M = Pd, Pt; X = Cl, Br

The interaction in these cases has been clearly established by careful X-ray diffraction studies.

Of the elements in the cobalt group, only cobalt itself has been studied with respect to its behavior in

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Scheme III

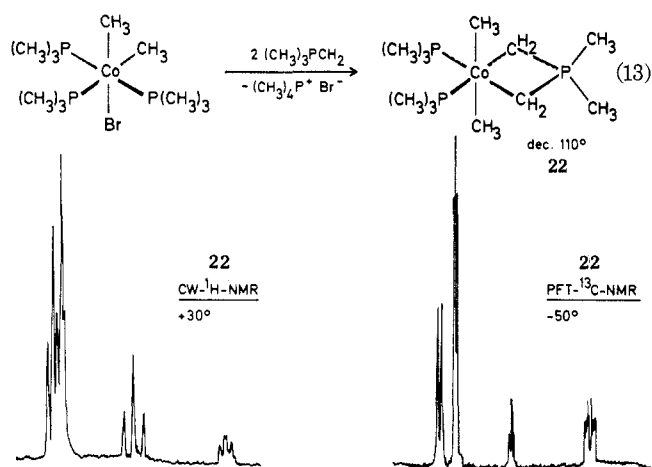
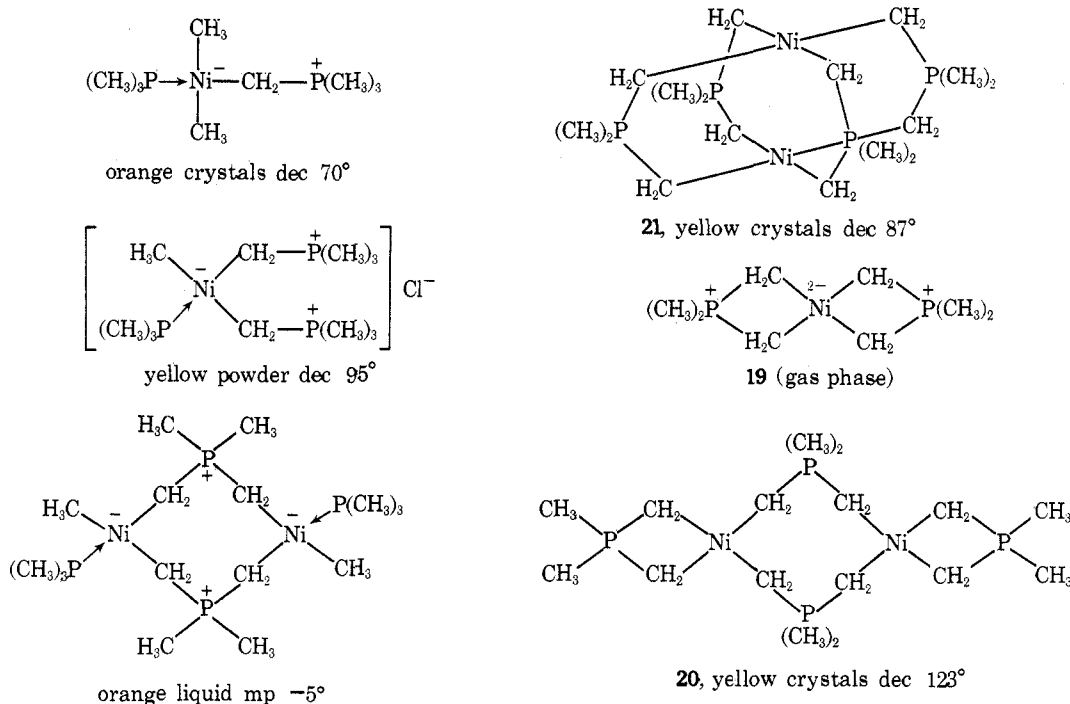


Figure 3.

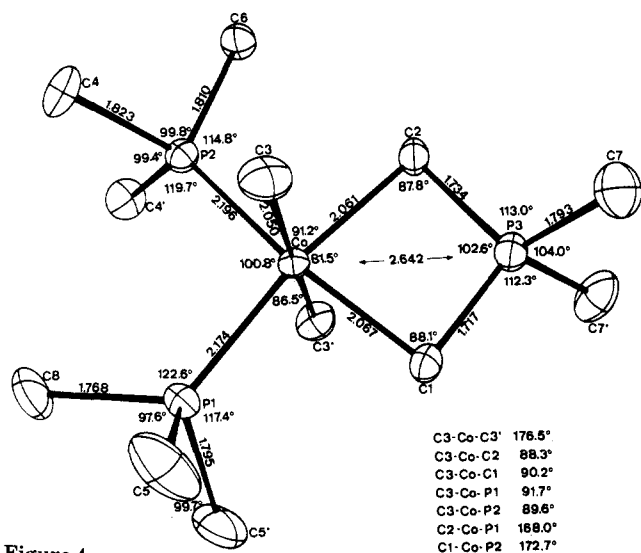
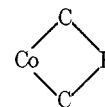


Figure 4.

reactions with ylides.⁶⁹ An important example of ylide coordination to an octahedral d⁶ metal center was detected as part of a broader series of experiments, and its structure has been investigated in considerable detail by spectroscopic and diffraction methods.^{72,81} As with some of the complexes of the chromium group, the ylide in **22** was found to function as a chelating ligand occupying one octahedral edge but with significant stereochemical differences in the configuration of the four-membered ring compared to that in the nickel compound **20**. Whereas the tilted structure in **20** suggests a pseudo-phosphaallyl type of interaction, the planarity of the



ring for the cobalt species suggests a more regular σ -type bonding (Figures 3 and 4).

Iron, manganese, and vanadium and their homologs have attracted relatively little attention and only the reactions of their carbonyl compounds with ylides have been thoroughly studied.⁸²⁻⁸⁴ Much more information is rapidly becoming available, however, on the ylide complexes of chromium, molybdenum, and tungsten. Among syntheses of a wide range of compounds, a recent report⁸⁵ on that of

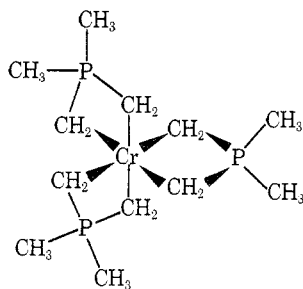
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chromium(III) tris(dimethylphosphonium bis-methylide) seems to be of special significance. In this octahedral d^3 complex, $(\text{CH}_3)_2\text{P}(\text{CH}_2)_2^-$ again appears as the sole ligand comprising all six Cr-C σ bonds. The stability of this molecule shows the great potential of metal ylide chemistry, from which many more exciting results are expected.

The author gratefully acknowledges the cooperation of a series of coworkers, who have contributed to the work from his own laboratory reported in this Account.

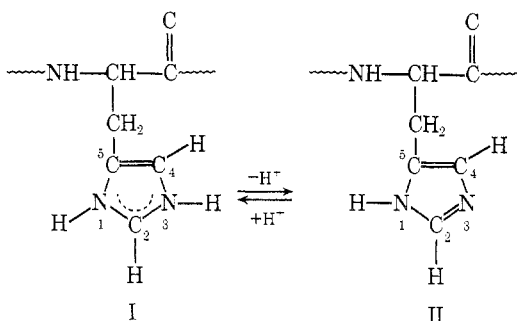
Observation of Histidine Residues in Proteins by Means of Nuclear Magnetic Resonance Spectroscopy

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The imidazole ring of histidine plays a critical role in the function of numerous proteins. The unusual importance of this amino acid stems from its acid-base properties. Histidine is the only amino acid whose side chain can serve either as an acid (I) or as a base (II) in the physiological pH range.



Knowledge of the environments and pK values of key histidine groups in proteins is of interest for learning how proteins work. In many cases one can obtain inferential data from pH-rate profiles of enzymes or from the pH dependence of the chemical modification of histidine residues. However, direct spectroscopic observation of the histidine residues is preferable whenever possible. Only limited success has been achieved with uv spectroscopy of histidine residues, because the histidine spectrum is weak and overlaps the region of stronger aromatic transitions.¹

John L. Markley was born in Denver, Colorado, in 1941. He received his B.A. degree from Carleton College and the Ph.D. from Harvard University. He worked as a research chemist at Merck Institute, then as NIH Postdoctoral Fellow at Lawrence Berkeley Laboratory with Melvin P. Klein and Melvin Calvin, and since 1972 has been Assistant Professor of Chemistry at Purdue University. His research interests largely concern the structure and function of biological macromolecules, especially proteins. Aside from research, he is a mountaineer and a photographer, and was a member of the first party to kayak the length of the Mahaweli Ganga River in Ceylon.

In 1964, as part of the first proton NMR investigation of proteins at 100 MHz, M. Mandel reported the detection of a composite signal from the imidazole C-2 protons of the histidine residues of ribonuclease A.^{2,3} In a prophetic statement, he concluded that, "This provides us with a window to observe the active site [histidines] under various conditions." A year later, J. H. Bradbury and H. A. Scheraga resolved peaks corresponding to three of the four individual histidines of ribonuclease A (using computer averaging at 60 MHz) and published titration curves for these.⁴

Encouraged by these successes, D. H. Meadows, J. S. Cohen, O. Jardetzky, and I embarked on extensive NMR studies at 100 MHz of the histidine residues of several proteins. This led to the elucidation of titration curves for all four histidines of ribonuclease A, the four histidines of staphylococcal nuclease, and the single histidines of chicken and human lysozyme.⁵ These and subsequent studies carried out in a number of laboratories concretely exemplify the value of NMR spectroscopy in protein chemistry.

Detailed reviews of much of this work have been published.⁶⁻⁹ In recent years, investigations have been extended to other proteins, and it is clear that NMR spectroscopy is the method of choice for observ-

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