GRAPHITE INSERTION COMPOUNDS AS CHEMICAL REAGENTS IN ORGANIC CHEMISTRY

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Abstract—The main properties of graphite and graphite compounds will be summarized. Special attention will be devoted to lamellar compounds, since many derivatives are known or were recently discovered.

It is interesting to investigate the chemical behaviour of graphite intercalated molecules for several reasons. It should be possible to make heterogeneous reactions in various solvents where the substrate is dissolved. Selective reactions can be expected since they occur on the surface. It would be interesting, too, to perform reactions in the interlamellar space.

Some examples will be given to illustrate or discuss these points. Reduction with potassium-graphite, halogenations with graphite-bromine or graphite SbCl₃ are examples of reactions performed by lamellar compounds. The behaviour of graphite electrolytic lamellar reagents will be presented, with the more recent results obtained in our laboratory. Strong inorganic acids such as H₂SO₄, HClO₄, H₃PO₄ may be intercalated under oxidizing conditions and give rise to electrolytic lamellar compounds. The deep blue compound C₂₄SO_{4.2}H₂SO₄ is particularly interesting. It allows esterification of a carboxylic acid at room temperature in cyclohexane solution. It plays two combined roles: that of an acid catalyst by activating the carboxylic acid and that of a dehydrating agent by reacting with water. Thus this graphite compound is not merely a catalyst. Some other of its reactions will be presented.

It is clear that the chemical behaviour of graphite intercalated molecules may differ in various ways from that of the non-intercalated reagents, giving reagents of potential interest in organic chemistry.

INTRODUCTION

The preference of organic chemists to carry out a reaction in an homogeneous medium is well known. However, during these last ten years there has been an increasing interest in reactions occuring between two phases, especially when one phase is a solid one.

The main advantage is the ability to recover by filtration one of the components of the system after reaction, as in the Merrifield synthesis of peptides. In some cases it can be interesting to have a small or null concentration of an agressive reagent in the reaction medium. This can be realized if the reagent is more or less tightly bound to a solid support. In other cases it can be expected that reactions occuring at the surface of a solid could be more selective than in an homogeneous medium.

I will present some results that we obtained by using lamellar graphite compounds. This work was possible thanks to a fruitful collaboration in Orsay between my laboratory and the laboratory of Inorganic Physical Chemistry (Pr Mazières, Dr Setton).

We can expect several consequences of this type of research. Graphite should be useful as a solid carrier for a reagent, especially if it is very reactive. Heterogeneous reactions can be made in many kinds of solvents. If the reaction occurs at the surface some specificity should be expected. Last point: is it possible to carry out reactions in the interlamellar space? Before discussing our main results, I will briefly introduce the area of interstitial compounds in graphite. Several reviews have appeared on the subject.¹⁻⁴

GRAPHITE STRUCTURE

The structure of graphite is well known. Graphite crystallises in a layer structure. In each layer carbon atoms are tightly bound to three other atoms. These bonds are shorter than carbon single bonds. The layers are bound together by weak forces, with a separation of 3.35 Å (Fig. 1). Alternate layers are displaced relative to

each other. Two kinds of graphite are known. The hexagonal modification is such that every second layer is superimposable (stacking sequencies A B A B...). In rhombohedral graphite the stacking sequences are ABC ABC

Graphite can give rise to two kinds of derivatives. Some non-conducting compounds of graphite are known. Oxidation gives graphite oxide in which the aromatic character is lost. The structure of these polymeres is not well defined. Graphite monofluoride CF was prepared too and its structure recently established.5 The second kind of graphite derivatives are the lamellar compounds which retain electrical properties of graphite. A layer of reactant can be intercalated between two carbon layers. A number n of carbon layers can indeed separate two reactant layers. This number n is usually called the stage of the lamellar compound. For example, the insertion of potassium in graphite was carefully studied by Rudorff and Schulze and five stages were observed. Stage 1, which is the most concentrated, can be obtained with potassium. For other compounds such a high concentration cannot be

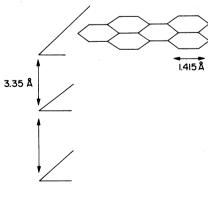


Fig. 1.

obtained and it is the second or even higher stages which are the most concentrated forms.

The structure of the reactant layer can be inferred from electrical and X-ray measurements. In general the monolayer does not retain the structure of the solid reactant nor does it assume a random arrangement as in the liquid state. The molecules or atoms R are arranged on a lattice which is closely related to the vicinal graphite lattice. The triangular or hexagonal arrays are known, giving a C₁₂R or C₈R stoiechiometry at stage 1. The spatial orientation of molecules between the layers was studied too. It is interesting to point out that the distance between two carbon layers can change according to the nature of the inserted compound.

INTERSTITIAL COMPOUNDS

What are the compounds which can be intercalated in graphite? There is a large number of inorganic or organic substances which can be placed between carbon layers. The intercalation can be effected spontaneously or by electrolysis. In Fig. 2 are reported some spontaneous graphite compounds. Halogens, metals, salts or oxides can be intercalated. There are some exceptions: for example Sb Cl₅ is inserted but not Sb Cl₃, Sm Cl₃ but not Pr Cl₃.... It is quite evident that the list of lamellar compounds is of great interest to the organic chemist. Some cases of interest are pointed out on Fig. 2. Mixed lamellar graphite derivatives are known too, for example graphite, FeCl₃, N₂O_{5.5} The electrolytic compounds are prepared by electrolysis and have the general formula indicated in Fig. 3. This graphite has been oxidized and reacted with one mole of reactant RH. The modified graphite incorporates additional intact RH molecules. Many inorganic or organic acids are able to form lamellar compounds as well as some amines.

This introduction shows the great potential of graphite derivatives for organic chemistry. When we started to investigate this field, several years ago, we looked on what was done. The main results had been obtained by the use of potassium-graphite as catalyst or reagent in several reactions.⁴

Recently, Lalancette et al.⁷ used potassium-graphite for reduction of some ketones. It found that the stereochemistry of reduction of camphor in THF is reversed by respect to the metal reduction. It was interpretated as the result of specific absorption of the

Spontaneous insertion in graphite

$$\begin{array}{l} \underline{\text{Li}}, \ \underline{\text{No}}, \ \underline{\text{K}}, \ \text{Rb}, \ \text{Cs}, \ \text{Sr}, \ \text{Bo}, \ \text{Sm}. \\ \\ \underline{\text{Br}_2}, \ \overline{\text{ICL}}. \\ \\ \underline{\text{CrO}_2\text{Cl}_2}, \ \underline{\text{CrO}_2\text{F}_2}, \ \underline{\text{UO}_2\text{Cl}_2}, \ \underline{\text{UCl}_4}, \ \underline{\text{FeCl}_3} \\ \\ \underline{\text{AlCl}_3}, \ \overline{\text{ErCl}_4}, \ \underline{\text{CuBr}_2}, \ \underline{\text{AlBr}_3}, \ \underline{\text{SbF}_5}. \\ \\ \underline{\text{CrO}_3}, \ \overline{\text{Sb}_2\text{O}_4}, \ \underline{\text{MoO}_3}, \\ \\ \underline{\text{Sb}_2\text{S}_3}, \ \overline{\text{CuS}}, \ \overline{\text{Fe}} \ \underline{\text{S}_2}, \ \overline{\text{WS}_2}. \\ \end{array}$$

No spontaneous insertion in graphite

$$\label{eq:continuous} \begin{split} &\text{TiCl}_4 \ , \ \text{SnCl}_4 \ , \ \text{SOCl}_2 \ , \ \text{PrCl}_3 \ , \ \text{SbCl}_3, \ \text{NiCl}_2 \ , \ \text{PtCl}_2. \end{split}$$

Fig. 2.

Graphite electrolytic lamellar compounds

$$C + RH \longrightarrow CnR$$
, $_{2-5}RH + \frac{1}{2}H_2$
 $n = 24$ NO_3H , CIO_4H , SO_4H_2
 PO_4H_3 , $(FH)_2$
 $n = 75$ $CF_3 CO_2H$
 $n = 900$ NH_3 , CH_3NH_2
 $Fig. 3$.

ketone on the surface. The reduction then occurs by a two-electron transfer from the potassium-graphite, as in an electrolytic process.

HALOGENATING REAGENTS

Our initial idea was to perform bromination on a small scale with a reagent easy to handle. We worked⁸ on samples of C₈Br, C₂₄Br, C₄₈Br. In the vial appear some bromine vapours above the solid. Nevertheless it is very easy to weigh, especially after cooling, since vapour pressure decreases strongly. First we performed brominations on small amount of ketosteroids by using acetic acid as solvent. The treatment is easy, there is only a filtration and an extraction to recover the bromosteroid. Other cases were studied, for example cyclopentene gives trans 1,2-dibromo cyclopentane with good yield. We used this reagent to solve a monobromination problem (Fig. 4). This is an example where a specificity is associated with a graphite reagent. It is possible that the bromination occurs mainly on the surface of the graphite and is related to the observation of Pincock et al. about the catalytic effect of graphite on binaphthyl racemization.

We prepared several samples of graphite-bromine and we studied the release of bromine in a solvent such as chloroform. The bromine is never quantitatively recovered. There is always residual bromine, a known phenomenon. We found that the residual bromine increases with time. In addition an aged sample is much more selective. This was investigated with 1,1'-binaphthyl. We could prepare selective reagents more rapidly by washing out with CCl4. The superficial bromine is then

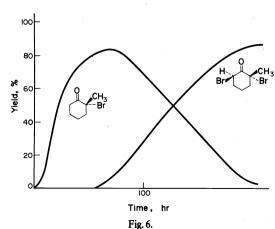
Fig. 4. From Ref. 8.

removed from the fresh sample. For example, the monobromination of 2-methyl cyclohexanone is not perfect (Fig. 5). But if we first wash the bromine-graphite we can obtain almost pure monobromoketone with a high conversion yield (Fig. 6). We have not further explored this area but it seems that some synthetic applications can be expected. As chlorinating reagent we looked for C₂₄SbCl₅ which is a compound easy to make and very stable. We wanted to compare its behaviour with free SbCl₅, since we found unexpectedly that it is very easy to chlorinate bromocycloalkanes stereospecifically by SbCl₅. Secondary and tertiary bromides react easily at room temperature. In the acyclic series there is no stereospecificity.10 We observed a transposition in the halogenation of the tertiary bromides in the cases where we could demonstrate it. The structure of the dihalides could be established by ¹³C spectroscopy.

Now what about the properties of the lamellar compound? (Fig. 7). If we stir it¹¹ in chloroform or CCl₄ solution with an organic substrate we always have a slow reaction. With acyclic bromides we observed only halogen exchange, the chlorine derivative being obtained. This is very different from what we obtained in homogeneous conditions. In one case, with a tertiary halide the α -chlorination was the predominant reaction (Fig. 7).

 Br_2 (lequiv.), CCl_4 or $\mathrm{C}_8\mathrm{Br}$ fresh, CCl_4

Fig. 5.



	Substrate RX	RCL		RX	Dihalide	
ı	n-C ₆ H ₁₃ CH-CH ₃ Br	n-C ₆ H ₁₃ -CH-CH ₂ Cl	98%	2%	_	
2	-Br	сι	60%	5%	Cl Br 35%	%
3	—Br		62%	20%	Cl Br 189	%
4	CH ₃	CH ₃	25%	-	CH ₃ Cl Br	%
5	C ₆ H ₅ -CH ₂ -CH ₂ -Br	c _e H ₅ -CH ₂ -CH ₂ -C	30%	70%	_	
6	C ₆ H ₅ −ÇH−CH ₃ Br	c _e H _s -cH-cH _s	98%	2%	1	
7		<u></u> -сı	86%	14%	_	
8	<i>n</i> –C _e H _{I3} CH −CH ₃ OTs	n-C ₆ H _{I3} CH-CH ₃ Cl	15%	85%	_	
9	OTs		5%	90%	Cl 59	,
10	_OTs	<u></u> —сі	22%	78%	_	

Fig. 7. From Ref. 11.

It appears then that the behaviour of inserted SbCl₅ is very different from free SbCl₅. This is an important conclusion; C₂₄SbCl₅ acts not only as carrier but also by its electronic or physical properties. This fact can be useful for other interstitial reagents.

When C₂₄SbCl₅ performs substitution on bromocyclohexane we are sure that the reaction does not occur via cyclohexene, which gives different products. An ionic step seems reasonable.

CrO₃-graphite. Several years ago we tried to prepare and study CrO₃-graphite, but a publication of Lalancette⁷ appeared, describing interesting results. It is possible by heating with a primary alcohol in toluene to obtain aldehydes selectively. Secondary alcohols are not attacked. The reagent is now commercialized under the trade name of Seloxcette.

Recently the true nature of the reagent was questioned by Ebert *et al.*¹² who showed that the procedure used to intercalate CrO₃ gives in fact a superficial deposit of Cr₃O₈. It remains to investigate the chemical properties of intercalated chromium trioxide which can indeed be obtained by working in the presence of acetic acid.¹²

Cl₃Al-graphite. The compound was used as a Friedel-Crafts catalyst and compared with Cl₃Al. ¹³ The alkylation of aromatic systems is more selective with the graphite catalyst. It gives less polysubstituted reaction products.

Electrolytic lamellar derivatives. Sulfuric acid has many catalytic properties. It is a strong acid which can be dangerous for labile organic molecules, and we were curious to see what would be the behaviour of the sulfuric acid-graphite. The preparation is described in Fig. 8. Each block of 24 carbon atoms looses one electron in the electrolysis. The positive ion is neutralized by SO₄H⁻coupled with the reduction of a proton. Two sulfuric acid molecules are then inserted. This blue graphite compound is easy to handle and to store.

We investigated it for esterification, and we were surprised to see its good and smooth catalytic properties. We worked in cyclohexane at room temperature¹⁴ and

$$C_{24} \longrightarrow C_{24} \stackrel{\oplus}{+} + e \stackrel{\ominus}{=}$$

$$C_{24}^{\oplus} + SO_4H_2 \longrightarrow C_{24} \stackrel{\oplus}{+} SO_4H + H$$

$$C_{24}SO_4H \cdot$$

$$H^{\oplus} + e^{\ominus} \longrightarrow H \cdot \frac{1}{2}H_2$$

$$C_{24}SO_4H /_2SO_4H_2 \longrightarrow C_{24}SO_4H, _2SO_4H_2$$
Fig. 8.

used equimolar amounts of an alcohol and of a carboxylic acid (Fig. 9).

The blue colour of the graphite-bisulfate disappears rapidly and turns tarry-brown. We checked the reaction at various time intervals by analyzing the solution by VPC. In the case of insoluble starting material the solid progressively dissolves. At the end point of the reaction the ester is isolated, after filtration of graphite, by evaporation of solvent.

In this way we obtained yields close to 90% within one to 20 hr according to the structure of the reactant. Primary alcohols or benzylic alcohols are rapidly esterified, secondary alcohols are esterified more slowly. Some

Acid	Alcohol	% Time ester (hr)	
нсоон	CH3CH2CH2CH2OH	98	ı
	CH₂OH	98	Ι.,
	—он	98	17
	OH(-)	98†	17
CH₃COOH	CH3CH2CH2OH CH3CH2CH(CH3)CH2OH	97 98	22 17
	CH₂OH	94	17
	ОН-ОН	87	17
C ₆ H₅CH₂COOH	C ₆ H ₅ CH(OH)CH ₃ CH ₃ CH ₂ CH(CH ₃)CH ₂ OH	96 95	0.5 26
	CH ₃ CH ₂ CH(OH)CH ₃ (+)	74‡	50
COOH HOCOCH ₂ COOH HOCO(CH ₂) ₃ COOH	CH ₃ CH ₂ CH(CH ₃)CH ₂ OH C ₆ H ₅ CH ₂ OH(2equiv) C ₆ H ₅ CH ₂ OH(2equiv)	53 94 96	17 17 17
HO-C-COOH HO-C-COOH	CH ₃ OH (2equiv)	99‡	60
н с _е н _з сосоон	OH(-)	50 [‡]	!7

[†]Identifications were made by ir, nmr, and comparison with authentic samples. Vpc analyses were run on a Perkin-Elmer F11 chromatograph (2 m column, Carbowax 20M 15%). Yields are calculated from the isolated ester.

Fig. 9. From Ref. 14.

tertiary alcohols have been investigated. We found that alcohols can be formylated by the same procedure.

We could use this procedure with acids other than formic or acetic acids. However, benzoylation is difficult. Diacids give the diester. We could change the nature of the alcohols. However very labile alcohols like geraniol give tars.

What is the mechanism of this esterification? We made an interesting observation: if the graphite sulfuric acid is stirred in the solvent with acetic acid, the latter disappears rapidly from the solution. The graphite gathers as a brown solid.

All the acetylating properties are localised on the solid, as was demonstrated by using it in an acetylation experiment. It is quite sure that a superficial combination of sulfuric and acetic acids is formed and that the reaction occurs on the solid phase.

It seems therefore most probable that a very reactive species is formed from the acid with the graphite bisulfate, as is the case when acetic acid or its anhydride is mixed with sulfuric acid. This species appears to be rather tightly bound to the solid support since: (i) the change in color indicates strong perturbations in the electronic distribution in the bulk of the solid reagent; (ii) the EPR spectrum of graphite bisulfate shows significant modifications after treatment by acetic acid: whereas the signal from the blue bisulfate is Dysonian and very narrow (A/B = 1.7-2.2, depending on the type of pyrocarbon used, $\Delta H = 0.250-0.350$ G peak-peak), that from the sample after contact with pure acetic acid is practically symmetrical and much wider $(A/B = 1 \cdot 1 - 1 \cdot 3 \Delta H = 0 \cdot 70 -$ 1.2 G), indicating a significant localization of the paramagnetic electrons.

Hydrolysis of graphite bisulfate gives graphite oxides which are known to be hydrophilic. The second role of the reagent in the esterification process may find its origin in this property and the graphite bisulfate is not merely a catalyst since it is modified by the water formed as the reaction proceeds. The esterifying capacity of graphite bisulfate can be estimated to be 5.5×10^{-2} mol of acid and alcohol per gram.

Acids more bulky than acetic acid (phenylacetic acid, octanoic acid) do not show the same affinity for the graphite-bisulfate. A selectivity effect can then be expected for the esterification of a mixture of unhindered and hindered acids. We looked for other properties of graphite-bisulfate. We found some cases of smooth preparation of ketals when methanol or glycol is used. An interesting procedure is the use of ethylorthoformate which allows in our standard reaction conditions the preparation of many ethyl esters from acids. Reactions where there is no water formation should be interesting for graphite-bisulfate, which would play a true catalytic role. For that purpose we investigated the case of cyclisation of geranic acid into cyclogeranic acid (Fig. 10). The reaction is slow but gives good yields of the non-conjugated isomer. 15

CONCLUSION

There are many researches to do in the area of lamellar compounds. We are working with derivatives such as perchloric or phosphoric acid, CrO₂F₂ and MoCl₅.

Nitric acid-graphite is under investigation, too. We prepared it by exchange with graphite-bisulfate. It is a mild nitrating reagent.¹⁵

What is the future of this field? It is too early for giving an answer. The first results indicate that selective reagents

[‡]Esterification occurs with retention of configuration.

Fig. 10.

should be found. The question of performing reactions inside the layers is left open. However, it must be noted that organic molecules can be intercalated in some cases.

A catalytic activity of intercalated graphite compounds with transition metal derivatives would be of great interest; first results have been recently published.¹⁶

Graphite is not the only family giving rise to insertion. Many inorganic materials are able to intercalate organic or inorganic molecules, ¹⁷ and interesting developments should also be expected in such systems.

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