Osmium Tetroxide and Its Applications

By W. P. Griffith

Department of Inorganic Chemistry, Imperial College, London

Osmium tetroxide, OsO_4, is the most important and most easily prepared compound of osmium. It has a number of specific applications in organic chemistry and in biochemistry, and it is with these that this article is chiefly concerned; it is also a useful source of osmium compounds. It is remarkable in that it is one of the few volatile oxides of a heavy metal and that although the osmium is octavalent (of all elements only osmium and ruthenium reach as high an oxidation state) it is a reasonably controllable oxidising agent. It is from this latter property that most of its applications derive.

Discovery and Preparation

The compound was discovered in 1803 by Smithson Tennant (1761–1815), and in the same year he isolated metallic osmium from it (1). Fusion with alkali of the black residue remaining after treatment of native platinum with *aqua regia* followed by extraction and acidification of the melt gave

> "a pungent and peculiar smell . . . from the extrication of a very volatile metal oxide; and, as this smell is one of its most distinguishing characters, I should on that account incline to call this metal *Osmium*" (1) (οσμη—smell, odour).

Industrially, OsO_4 is made from crude platinum concentrates by oxidative acid distillation and is then separated from ruthenium tetroxide. In the laboratory it is best made by direct oxidation of osmium metal (2) or by the acid distillation with chlorate of almost any osmium compound.

Toxicity

The solid has an appreciable vapour pressure at room temperature and should be handled with care. The vapour is poisonous (maximum permitted atmospheric level 2×10^{-6} g/m³). It attacks the eyes, causing blurring of vision and, in very severe cases, temporary blindness, and it also attacks and irritates the nose and throat linings and may exacerbate bronchial conditions. Fortunately it has a characteristic, penetrating, rather ozone-like smell and this, together with its irritant effects, makes accidents with it rare. In the event of OsO_4 vapour attacking the eyes or the skin the remedy is washing with copious quantities of water. Spilled OsO_4 may be reduced by dissolving it in alkali in 50 per cent water-ethanol solution, and the non-volatile osmate salt may then be washed away.
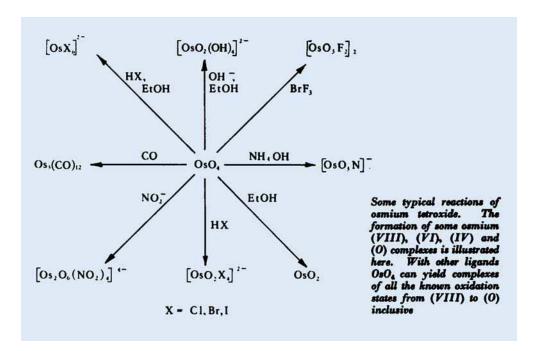
Physical and Chemical Properties

The properties of OsO_4 have been reviewed by Griffith (3). The solid forms pale yellow monoclinic crystals (M.P. 40.6°C, B.P. 121.2°C, density 4.906). It is fairly soluble in water (7.2 g/100 ml at 25°C) and extremely soluble in inert organic solvents (e.g. 350 g/100 ml. of carbon tetrachloride). It exists in the gaseous, solid or solution state as discrete molecular tetrahedra (Os—O distance 1.717 Å). The thermodynamic properties of OsO_4 have been reviewed (4).

In almost all of its chemical reactions, a number of which are summarised in the diagram, OsO_4 is reduced to compounds containing lower oxidation states. With ammonia, however, the tetrahedral osmiamate ion $[OsO_3N]^-$ is formed, which is isoelectronic with OsO_4.

Applications in Organic Chemistry

The valuable function of OsO_4 in the oxidation of olefins has been known and applied since 1913, and now constitutes one of

Some typical reactions of osmium tetroxide. The formation of some osmium (VIII), (VI), (IV) and (0) complexes is illustrated here. With other ligands OsO_4 can yield complexes of all the known oxidation states from (VIII) to (0) inclusive

the major industrial and laboratory uses of the compound, particularly for reactions of steroids and sugars. The subject has been well reviewed by Rylander (5) and also by Fieser and Fieser (6). It is used mainly for the *cis*-hydroxylation of olefinic double bonds to give glycols, for which purpose it is the smoothest and most efficient general reagent known. It tends to react faster with strained olefins, particularly in the presence of pyridine (7). Aromatic hydrocarbons are hydroxylated only at the most reactive aromatic site (e.g. phenanthrene at the 9,10 position (8)).

The reagent may be used either alone in an inert solvent, the resulting osmate (VI) ester being decomposed by bisulphite or hydrogen sulphide (6,7), or, more commonly and economically, in the presence of an additional oxidant such as chlorate, hydrogen peroxide or periodate. These regenerate the OsO_4 which is therefore functioning as a catalyst. There is little doubt that cyclic osmate (VI) esters are involved in these reactions, and a recent X-ray study showed that mono-esters are dimeric (I) with a dioxo bridge, the osmium having square-based pyramidal coordination (8). The overall reaction is shown below:

(I)

The catalytic conversion of olefins to glycols by osmium tetroxide

Examples of simple hydroxylations with OsO_4 are the production of glycerol from allyl alcohol and of ethylene glycol from ethylene. The compound has been used in the synthesis of such species as cortisone, progesterone, and of reserpine-type alkaloids, and also in the degradative investigation of natural products such as columbin (6). The glycol cleavage properties of periodate may be used together with the oxidising properties of OsO_4 to convert olefins to aldehydes (e.g. trans-stilbene to benzaldehyde, cyclohexene to adipaldehyde), to ketones or to epoxides (10).

In Biochemistry

The compound is extensively used (normally in 2 per cent aqueous solution, often called "osmic acid") for cell and tissue studies, its unique fixation and staining properties having been recognised and used since 1861. It is used for both visible and electron microscopy of biological materials, but now the latter application is probably the more important.

The purpose of *fixation* is to "freeze" cells without destruction or disruption of their organisation or structure; *staining* is necessary for the resolution of cellular structure by increasing the apparent density of some parts of the tissue only. OsO_4 is unique in that it both fixes and stains biological material. For the electron microscopist its most important functions are the preservation of sub-cellular ultrastructure and its ability to fix and stain membranes. For staining purposes it is often used with polar species such as uranyl or lead ions. The normal method used is to pre-treat the tissue with aldehydes, then to treat it by immersion in a dilute aqueous solution of OsO_4 (or the tissue is exposed to OsO_4 vapour) followed by washing, additional staining if required, dehydration with alcohol, embedding in resin and cutting into thin sections suitable for microscopy.

The mechanism of tissue fixation and staining by OsO_4 is far from clear, although it is generally accepted that the first step is the attack of double bonds in unsaturated lipids to give osmate (VI) esters. There is evidence that mono-esters of type (I) above may be involved, in which case the fixation property may possibly arise from the formation of dioxo bridges (9).

There are still many questions to be answered, however—whether mono- or di-esters are normally formed (12), and whether in the dehydrated tissue the osmium is further reduced to osmium (IV) and perhaps shifted away from the original double-bond sites. The resolution of these problems is important since OsO_4 is so extensively used, and it is necessary to know to what extent the fixed and stained tissue is representative of the once living organism.

Corrosion Prevention

Like some other heavy metal tetra-oxo species, osmium tetroxide in electrolytes has the property of passifying iron electrodes (13).

References

1 D. McDonald, *Platinum Metals Rev.*, 1961, **5**, 146; Smithson Tennant, *Phil. Trans.*, 1804, **94**, 411

2 G. Brauer, Handbook of Preparative Chemistry, Academic Press, New York, 1965, p. 1603

3 W. P. Griffith, Chemistry of the Rarer Platinum Metals, Interscience, New York, 1967; *Quart. Rev.*, 1965, **19**, 254

4 B. N. Goldberg and L. G. Hepler, *Chem. Rev.*, 1968, **68**, 229

5 P. N. Rylander, *Engelhard Ind. Tech. Bull.*, 1968, **9**, 90; F. R. Gunstone, *Adv. Org. Chem.*, 1960, **1**, 103

6 L. F. Fieser and M. Fieser, Reagents for Organic Synthesis, Wiley, New York, 1967, pp 475, 759

7 R. Criegee, B. Marchand and H. Wannowius, *Ann.*, 1942, **550**, 99

8 G. M. Badger, *Quart. Rev.*, 1951, **5**, 160

9 R. J. Collin, W. P. Griffith, F. Phillips and A. C. Skapski, *Biochim. Biophys. Acta*, 1973, **320**, 745; *J. Chem. Soc., Dalton Trans.*, 1974, 1094

10 R. Pappo, D. S. Allen, R. U. Lemieux and W. S. Johnson, *J. Org. Chem.*, 1956, **21**, 478

11 M. A. Hayat, Principles and Techniques of Electron Microscopy, Vol. I, van Nostrand, 1970

12 J. Riemersma, *Biochim. Biophys. Acta*, 1968, **152**, 718; E. D. Korn, *J. Cell Biol.*, 1967, **34**, 627

13 G. H. Cartledge, *Corrosion*, 1967, **18**, 316t