0033-4545/78/1001-1129 $02.00/0

COORDINATION COMPOUNDS IN ANALYTICAL CHEMISTRY

Harry M.N.H. Irving

Department of Inorganic Chemistry, University of Cape Town,
Rondebosch, Cape Town, South Africa

Abstract - Coordination compounds are used in almost every
branch of analytical chemistry. The factors which make them
specially suitable for gravimetric and titrimetric analysis,
for liquid-liquid extraction and various types of chroma-
tography (e.g. in both mobile or stationary phases in gas
chromatography) are illustrated by examples. Stereochemical
features, reaction kinetics, conformational changes, and ligand
field stabilisation are also shown to be relevant factors in
specific cases. The achievement of a measure of controlled
selectivity in the reactions of inorganic cations with organic
ligands is discussed in relation to recent work on complexones,
crown ethers, and cryptates, although the accidental discovery
of an unusual coordination compound that owes its usefulness to
an unexpected and unpredictable crystal structure is not over-
looked.

The most widely read Journals specializing in the field of analytical
chemistry carry nowadays a preponderance of articles on purely physical
methods of analysis, on automatic analyses of all kinds, on the analysis of
multi-component systems and on the relevant computational techniques and
statistical treatments.

This trend towards physical and automated methods is appropriate for many
routine analyses and often inevitable on purely economic grounds; but it must
not be forgotten that despite the progress that has undoubtedly been made in
elaborating entirely physical techniques for the determination of multi-
component systems, with automatic compensation and correction for inter-
element (matrix) effects by the use of individually programmed and dedicated
computors, there is still a great deal of analysis conducted appropriately
and unavoidably by chemical methods. Indeed, wet chemistry still forms the
basis for all the automated procedures using equipment such as the Technicon
Autoanalyser. In such procedures coordination compounds play a continuing
role and it is doubtless for this reason that the organisers of this the
XVIII th International Conference on Coordination Chemistry have chosen a
Plenary Lecture devoted to this general field.

The commonest task of the analyst is to determine quantitatively the amount
of some particular species (the analyte) originally present with others in a
matrix, and often present in small amount both relatively and absolutely.
To achieve this it is usually necessary to carry out a certain amount of
pre-concentration so that the amount of analyte available will be sufficient
to carry out the appropriate quantitative determination at an acceptable
level of precision. Interferences in this determination by all other
components of the matrix must be reduced below certain limiting levels by
separation procedures which may, to a greater or less extent, be incorporated
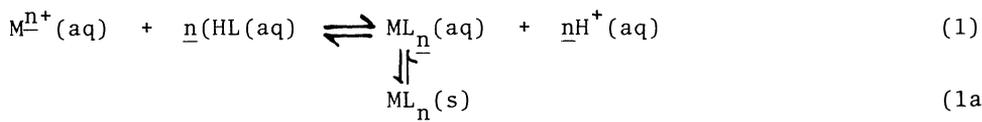or inherent in the pre-concentration stage.

Since our theme is to be the application of coordination compounds in
analytical chemistry it will be convenient first to consider their classical
use for the separation and determination of inorganic cations and anions
by precipitation. Here we look for a number of desirable characteristics,
viz. low solubility in water; freedom from co-precipitation and occlusion;
good filterability; stability towards the stages of washing and drying to
constant weight; and a stoicheiometric, or at least strictly reproducible
composition. To which one should add the ideal of specificity; the hope so
temptingly proffered with the introduction of Tschugaeff's dimethylglyoxime

as a reagent for nickel by Brunck in 1907 (Ref. 1); the goal so rarely
approached.

Low solubility is a consequence of a high lattice energy associated with a
low solvation energy. Although an increase in the thermodynamic stability
(formation) constant along a series of metal chelates is often associated
with increasing insolubility, this is far from being a determining factor.
For example, although the copper complex of dimethylglyoxime is certainly
more stable thermodynamically than the nickel complex (Ref. 2), the latter
is far more insoluble because of the special features of the packing of
discrete molecules in the crystal lattice which provides strong axial
Ni-Ni bonds through the lattice (Refs. 3 & 4). To be sure, the effect of
introducing heavy halogen atoms into a molecule is often to decrease the
solubility by what Feigl (Ref. 5) termed the 'weighting effect'; but it may
also increase the solubility by making crystal packing less energetically
favourable, or by reducing intermolecular assoication caused by hydrogen
bonding as illustrated by the R_f values of indigo and its 4,7-halogen subs-
tituted derivatives (Ref. 6).

Hydrophilicity due to the presence of coordinated water can usually be
reduced by replacing it by donor molecules of a less hydrophilic character.
This is illustrated by substances derived from aquated cations of copper(II),
cadmium and iron(II) in such compounds as $(Cuen_2^{2+})(CdI_4^{2-})$ and $(Cuen_2^{2+})(HgI_4^{2-})$
which are insoluble in water, ethanol and ether, or by $(Fe(bipy)_3^{2+})(CdI_4^{2-})$
which provides a very sensitive spot-test for cadmium. Other examples are
the well-known thiocyanato complexes containing coordinated pyridine such
as $M(SCN)_2 \cdot npy$ (M = Cu(II), Cd, Co(II), Fe(II), Mn, Ni, Zn; $\underline{n}$ = 2 or 4).
The virtues of large hydrophobic cations conjoined with large anions is
illustrated by such insoluble complexes as $(CH_3(C_6H_5)_3N^+)_2CdI_4^{2-}$,
$(Fephenan_3^{2+})(ReO_4^-)_2$ or $BH^+BiI_4^-$, where B is cinchonine or a similar hetero-
cyclic base.

The desirable features of coordination compounds in gravimetry are displayed
by many of the great variety of metal chelates that have been introduced
into analytical practice (Refs. 7, 8 & 9). In the reactions between a
cation M^{n+}, and a chelating agent, HL (usually a weak acid) we have to
consider the equilibria

$$M^{n+}(aq) \; + \; \underline{n}(HL(aq) \; \rightleftharpoons \; ML_n(aq) \; + \; \underline{n}H^+(aq) \qquad (1)$$

$$\Downarrow$$

$$ML_n(s) \qquad (1a)$$

and $HL(s) \rightleftharpoons HL(aq) \rightleftharpoons H^+(aq) + L^-(aq)$ $\qquad\qquad (2)$
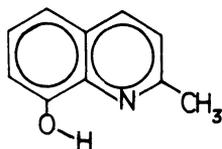
Water of solvation is omitted for the sake of simplicity. The position of
equilibrium will be determined by the pH and the relevant proton- and
metal-ligand formation constants β_{ML_n} and β_{HL} respectively. By a suitable
choice of pH and reagent concentration reaction (1) can be made to go
effectively to completion. For a given reagent and a series of cations (of
the same charge type), the position of equilibrium in equation (1) will
lie further to the right the more stable the complex ML_n. Providing only
that the lattice energy of the precipitate, $ML_n(s)$, shows no exceptional
behaviour, the pH at which precipitation reaches a predetermined value
(say 99.9%) will be progressively lower as β_{ML_n} increases, thus permitting

separations which may be adequate for many purposes. The metal chelate is
generally of stoicheiometric composition and can often be used directly as
a weighing form. Where this is not the case (e.g. with cupferron and the
nitrosonaphthols and some complexes of oxine, the precipitate may have to be
ignited to a definite oxide. Generally speaking, the more sparingly
soluble the reagent, the less soluble the corresponding metal chelate.
Since excess reagent must be used to ensure quantitative precipitation this

factor can introduce problems when washing the filtered-off precipitate
to remove excess reagent, and a good deal of effort has gone into
modifying the structure of some important precipitants (e.g. dimethyl-
glyoxime) with a view to increasing the solubility of the reagent without
increasing that of the metal complexes (Ref. 10).

If the metal-ligand bonds in a metal chelate are weakened by steric
factors a new feature is introduced. Thus while aluminium tris-(8-hydroxy-
quinolinate) is readily prepared as a yellow precipitate from water, the
corresponding complex with 2-methyl-8-hydroxyquinoline (I; R=CH$_3$) cannot be
prepared in aqueous solution (although
it does form in non-aqueous media).
The basic reason is that in order to
displace the equilibrium of equation
(1) to the right sufficiently to
compensate for the lowered value of
β_{ML_3}, the pH must be raised beyond the
level at which the competing reaction

$$Al^{3+}(aq) \;+\; 3OH^{-} \rightleftharpoons Al(OH)_3(s) \quad (3)$$

(I)
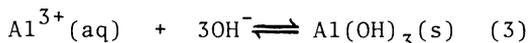
predominates, and aluminium hydroxide,
rather than aluminium tris-(2-methyl-8-hydroxyquinolinate), precipitates
first. This anomalous behaviour is also shown by other derivatives of
8-hydroxyquinoline (I; R=H) substituted in the 2-position(by alkyl or
aryl substituents) and by analogues in which steric hindrance to coordination
is caused by annelation which includes the 2-position (as with 2-hydroxy-
acridine or 9-hydroxy-1,2,3,4-tetrahydroacridine) (Refs. 11, 12 & 13).

This combination of circumstances is virtually unique for Al^{3+} since the
larger ions, Ga^{3+}, In^{3+} and Tl^{3+}, where steric hindrance would be expected
to be less pronounced, give normal tris-complexes. It is analytically
significant that the alkaline earths and divalent transition metals can all
be precipitated as bis-complexes with 2-methyl-8-hydroxyquinoline (I; R=CH$_3$)
thus providing a route to the determination of Mg^{2+} and Al^{3+} in admixtures.
Beryllium also forms an insoluble bis-chelate in spite of the fact that its
cation (radius Be^{2+} = 0.31 Å) is smaller than that of Al^{3+} (0.5 Å). This
is clearly the consequence of beryllium using 2s2p^3 hybridisation to form
a tetrahedral complex in which there can be no steric hindrance to coord-
ination from bulky 2-constituents since the two coordinating ligands now
lie in planes at right-angles to each other. Although a 2-methyl substituent
lowers the formation constant of complexes of 8-hydroxyquinoline or its
analogues with such cations as Cu^{2+}, Mg^{2+}, Ni^{2+}, UO$_2^{2+}$ and Zn^{2+}, substitution
in positions 5, 6 or 7 usually strengthens the metal-ligand bonds (Ref. 14).

8-Hydroxyquinoline is far from being a selective precipitant, and whereas
selectivity is certainly improved by replacing the donor oxygen by sulphur,
the resulting 8-mercaptoquinoline now suffers from the ease with which it
can be oxidised, a disadvantage shared by a number of analytically valuable
thiols (such as toluene-3,4-dithiol), by solutions of dithizone, and by a
group of dialkyldithiocarbamates which are best stored as their zinc
complexes until needed.

The lack of selectivity of 8-hydroxyquinoline can be turned to good
advantage when the problem is one of collecting a wide spectrum of cations
from a dilute solution - a problem of increasing importance in the study
and control of environmental pollution. Here its use as a 'scavenger'
can often be supplemented by other non-selective reagents and it lends
itself especially well to pre-concentrations by liquid-liquid extraction of
its metal chelates (Refs. 15 & 16). Vanderborght and Van Grieken (Ref. 17)
noted that whereas active charcoal will absorb many cations directly
(capacity 1 mg g^{-1} for Zn^{2+} or Cu^{2+}) it has a greater capacity for organic
substances and argued that a hydrophobic metal chelate in which the metal
is 'encapsulated' by an organic reagent should be absorbed more strongly,
especially if the ligand had an aromatic structure with Π-orbitals to
increase the strength of interaction with the active charcoal. They found
that the capacity of active charcoal for metal oxinates was some 30 times

greater than for the metals alone, and by using an excess of oxine
(2.5 - 25 ppm of oxine at pH ∿ 8) they could collect from natural waters
90 - 100% of transition metals, Cd, Hg, Hf and lanthanides, 80 - 90% of
Cu and Pb, 30% Ag, 0 - 20% Sb, less than 10% of alkaline earths with
virtually no alkali metals.

In addition to acting as 'scavengers' for a whole range of cations it is
possible to devise systems which are particularly efficient for some of
them. If pyrolidinedithiocarbamic acid is added to cobalt(II) buffered
at pH ∿ 4, the precipitate of tris-(pyrolidinedithiocarbamate)cobalt(III)
proves to be a most efficient collector for Cr(VI), Cd, Ni and Pb (over 90%
from initial concentrations of 0.1 mg l^{-1}), less good for Cu, Fe(II) and
Fe(III), and poor for Zn, Mn and Cr(III) (Ref. 18). The use of columns of
e.g. CuS and PdS to collect Pd(II) has recently been extended to the use of
chelating agents or complexes such as silver dithizonate, preferably
supported on columns of plastized foam material to improve contact and
increase flow rates. In the nature of things these are more specific in
their behaviour, limiting their collecting properties to those cations
capable of forming insoluble metal chelates and able to displace the
original metals (zinc, silver, etc.) under the experimental conditions
(Ref. 19). It has been known for over 70 years that a precipitate of
ammonium molybdophosphate (AMP) changes its composition if washed by a
solution of potassium nitrate, and that the replacement of ammonium by
potassium ions is reversible (Ref. 20). This ion-exchange behavious was
rediscovered at intervals and thoroughly studied by van Smit, by Meier and
Treadwall, by Thistlethwaite, and by Healey and his co-workers (Ref. 21).
Distribution coefficients are substantially larger than for a typical
cation exchange resin, Dowex-50 (see Table 1) and clean separations of

TABLE 1.   Distribution coefficients for univalent cations (Ref. 15)

Exchanger	$\underline{K}_D$, meq g^{-1}					
	Na$^+$	K$^+$	Rb$^+$	Cs$^+$	Ag$^+$	Tl$^+$
Ammonium molybdo-phosphate, AMP	0	3 - 5	192	5430	26	4300
Dowex-50 in the NH$_4^+$ - ion form	26	46	52	62		
Crystallographic radii, Å	0.95	1.33	1.48	1.69	1.26	1.44

Rb$^+$ - Cs$^+$, Na$^+$ - K$^+$, ^{90}Sr^{2+} and its daughter ^{90}Y^{3+} have been reported. It
has been proposed for treating fission wastes (Ref. 22), especially to remove
^{137}Cs, and to concentrate this isotope selectively from urine preliminary to
low-level β-counting (Ref. 23). If the AMP is admixed with an inert material
such as asbestos, improvements in the hydro-dynamic properties of a column
are made though at the expense of increased volume and decreased bed
capacity. Various organic polymers have been examined as binding materials
to produce columns suitable for the removal of Cs from Purex high-level
radioactive waste (Ref. 24), and beads of silica gel incorporating 65 wt. %
of AMP have been prepared with good chemical, thermal, and radiochemical
stability accompanied by good mechanical and hydrodynamic properties and
resistance to abrasion (Ref. 25).

Although ammonium molybdotungstate and tungstosilicate are too soluble for
similar use, Katil has shown (Ref. 26) that ammonium phosphotungstate can
be used to separate Cs$^+$ and Rb$^+$, and of the whole group designated by
$H_m XY_{12}O_{40} \cdot \underline{n}H_2O$ ($\underline{m}$ = 3,4, and 5; X = As, Si, P; Y = Mo, W, V), stannic
vanadophosphate has recently been studied for the separations In - Ga,

Mg - Ca, and Mn - Ni (Ref. 27). Many ferrocyanides have been examined for applications in radiochemical and other separations (Ref. 28), and a synthetic apatite of composition $Pb_7Sr_3(PO_4)_6(OH)_2$ has proved to be an excellent ion-exchanger for F^- (Ref. 29), though it may be felt that such coordination compounds should not come within the scope of this talk. Before leaving the topic of anion-exchanging materials I should mention that it must be at least 30 years ago that I examined Werner's classical wholly inorganic tris-chelate of cobalt(III), viz. tris[tetrammine-μ-dihydroxocobalt(III)]sulphate, $[Co(NH_3)_4(OH)_2]_3Co^{6+}(SO_4^{2-})_3$ as a possible anion-exchanger. Alas, it proved to be too soluble and showed no outstanding specific properties.

One last example of an unusual application of a solid coordination compound is the use of the highly insoluble zirconium selenite for the determination of fluoride ion. The selenite is labelled with ^{75}Se by neutron activation and made into a chromatographic column after admixture with powdered PTFE. On treatment with a solution containing fluoride ions, the activity of the eluent (0.25M-HCl) is a measure of the added fluoride (100 - 200 μg determined with ± 5% precision) in consequence of the reaction (Ref. 30);

$$Zr(SeO_3)_2 \; + \; 6HF \rightleftharpoons ZrF_6^{2-} \; + \; 6H^+ \; + \; 2SeO_3^{2-} \tag{4}$$
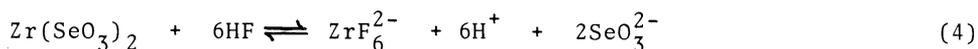
Most separation techniques involve some form of partition between two phases and we will consider in turn those properties of coordination compounds that are relevant to their use in gas-solid, liquid-solid, and gas-liquid chromatography along with the cognate field of liquid-liquid extraction. Up to 1970 most emphasis on the gas chromatography of metals was directed towards exploiting the volatility of particular metal chelates. The problem here is to achieve a coordination compound that can be vaporised at as low a temperature as possible and which is thermally stable. Much work has been carried out by using 1,3-diketones and their fluorinated derivatives for the gas chromatography of tris-chelates of Al, Cr(III), Sc, Rh and the lanthanides; not too much success has attended the gas chromatography of bis-chelates with the exception of that of beryllium bis-trifluoro-acetylacetone(II) which formed the basis of a procedure for determining beryllium down to 4×10^{-4} g in 10 - 100 mg samples of lunar dust and rock (Ref. 31). Hexafluorothioacetylacetone forms a number of volatile chelates (III; M = Cd, Cu, Fe(II), Ni, Pb, Pt, Zn)
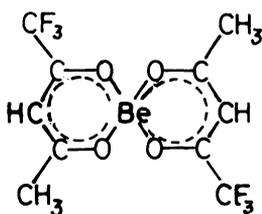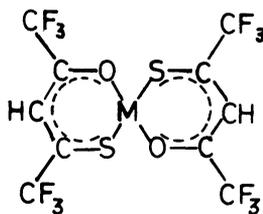

(II)   (III)

with low melting points ranging from 54.5°C (Zn) to 108°C (Cd) which lend themselves to gas-chromatographic separations (Refs. 32 & 33). Monothiotrifluoroacetylacetone has been used to determine Ni down to 10^{-11} g and bidentate and tetradentate β-aminoketonates have been used with Cu, Ni, Pd and Pt down to the picogram level (Refs. 34 & 35). Chelate complexes of diethyldithiocarbamic acid, $Et_2N \cdot CSSH$, have also been studied recently. Those of Fe(III), Co(III), Ni and Zn are highly stable thermally: complexes of Ag and Cu(II) are stable up to 240°C, and those of Co, Ni, Pd and Pt up to 300°C, many elegant separations have been achieved.

Quite another aspect of gas chromatography concerns the use of coordination compounds as the stationary phase. A coordination polymer such as (IV; M = Ni or Co(II)) has been found to have excellent thermal and chemical stability and can be used for separating a variety of aliphatic, aromatic

and heterocyclic bases.
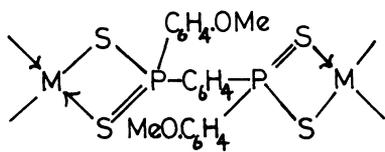
(IV)
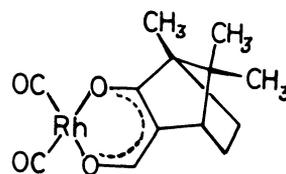
(V)

Retention volumes remained constant even after many hours use at 100°C

Fig. 1. Separation of nitrogen bases on a stationary phase of 5%
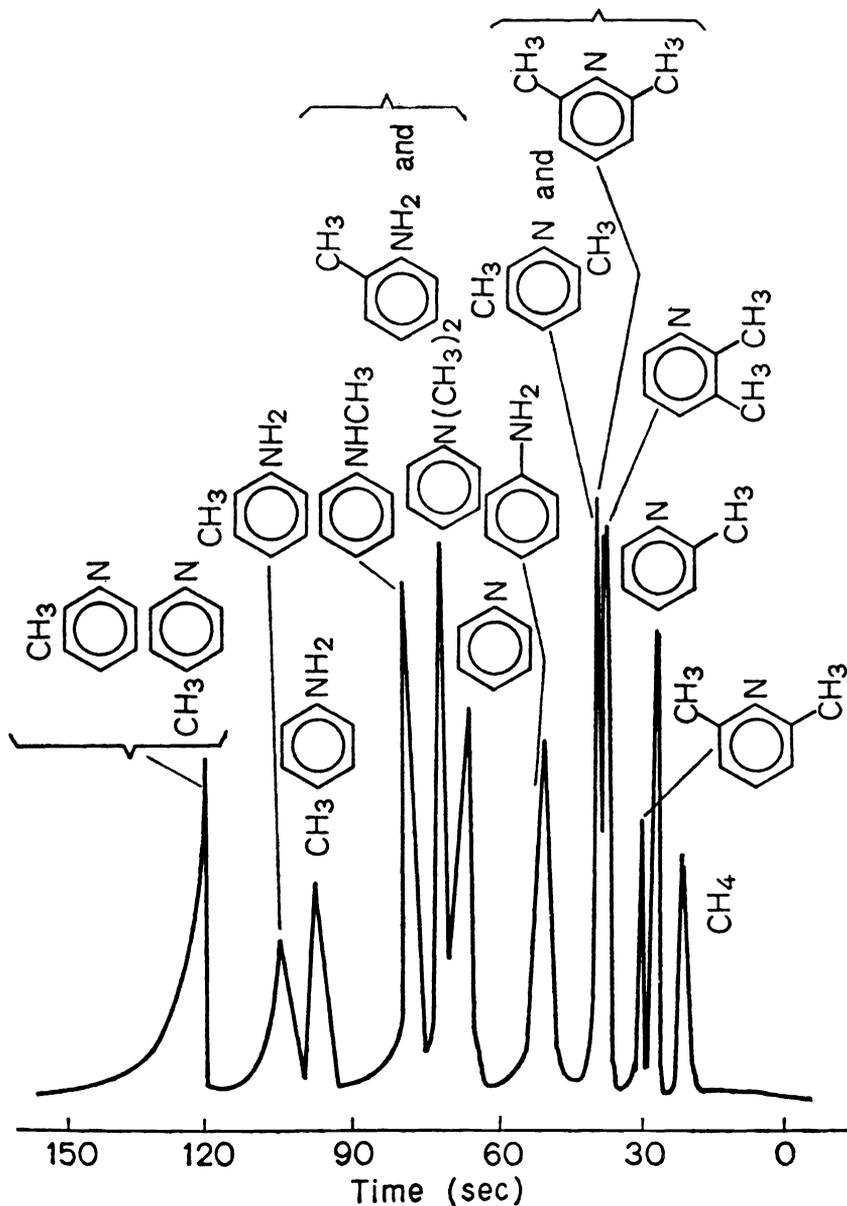   cobalt phthalocyanine on Sterling F.T.G., 10 m column
        with NH₃ + H₂ as carrier gas at 178°C (Ref. 38).

(Ref. 37). The use of cobalt(II) phthalocyanine (5% on Sterling F.T.G.)
has a further advantage in that it can exploit steric hindrance to
coordination. Thus, 2-methyl substituted pyridines are eluted before
pyridine itself (with its unhindered nitrogen atom) despite their higher
relative molecular masses (cf. Fig. 1) (Ref. 38).

The use of a silver salt in the stationary phase for the gas chromatography
of alkenes was one of the earliest examples of exploiting stereoselective
features in coordination (Ref. 39), and Gil-Av and Schurig have shown more
recently that dicarbonylrhodium(I)-3-trifluoroacetylcamphorate (V) provides
an excellent stationary phase for the gas chromatography of monoalkenes,
for complex formation is stronger and the effects of structural changes in
the alkenes are more marked in distinguishing between cis- and trans-, and
position isomers (Ref. 40).

There have been innumerable papers describing the applications of metal
chelates in column and thin-layer chromatography (cf. Ref. 41 for metal
dithizonates alone). The non-polar character, high thermodynamic
stability and intense colour of many such chelates lend themselves to
t.l.c., and by using uniform, ultra-thin layers (1 - 6 μm) produced by
the anodic oxidation of very pure aluminium foil, less than 1 ng of
several metals can be separated and identified as their dithizonates
(Ref. 42).

In the latest of a long series of papers, Ludwig and his co-workers have
studied the t.l.c. of chelates of thiodibenzoylmethane (VI) and noted
that although derivatives of the more polar acetonylthioamides (VII) are
less strongly coloured, they give significantly different R_f values (Ref.
43).

$$C_6H_5.C.CH_2.C.C_6H_5$$
$$\quad \text{O} \qquad \text{S}$$

$$R.C.CH_2.C.NHC_6H_4.X$$
$$\quad \text{O} \qquad \text{S}$$
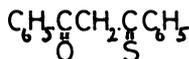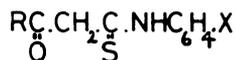
(VI)   (VII; X = H,CH$_3$, halogens, CN, etc.)

Yamamoto and Yamamoto have carried out a more detailed study of the
chromatography of the acetylacetonates of Al, Cr(III) and Co(III) which
are eluted in the order of their decreasing molar volumes; the results
are discussed in terms of the relevant solubility parameters (Ref. 44).

TABLE 2.   Thin layer chromatography of coordination compounds
on silica gel (Ref. 45)

Compound	Structure	R_f [a]	R_f [b]
Cu(acac)$_2$	square planar	0.30	0.08 - 0.65
Cr(acac)$_3$	octahedral monomer	0.93	0.77
Co(acac)$_3$	octahedral monomer	0.63	0.70
Fe(acac)$_3$	octahedral monomer	0 - 0.25	0.80
[Co(acac)$_2$]$_4$	octahedral polymer	0.0	0 - 0.11
[Ni(acac)$_2$]$_3$	octahedral polymer	0.0	0 - 0.12

[a] Elution with diethyl ether.

[b] Elution with benzene - diethyl ether - acetylacetone,
50:50:1.

Oksala and Krause examined the t.l.c. of coordination compounds such as
square planar Cu(acac)$_2$, the octahedral monomers, Cr(acac)$_3$, Co(acac)$_3$
and Fe(acac)$_3$, and the octahedral polymers [Co(acac)$_2$]$_4$ and [Ni(acac)$_2$]$_3$
and conclude that non-labile, coordinatively saturated complexes should
move with large R_f values on elution with solvents of moderate polarity,
provided there is no permanent dipole in the compound. Labile compounds

show increased $\underline{R}_f$ values when excess ligand was present in the eluent (Ref. 45). The authors note that "complexes capable of undergoing a ready expansion of coordination number are expected to show greater retention under similar conditions." Since $\underline{R}_f$ values can usually be correlated quite well with the distribution coefficients obtained in liquid-liquid extraction, this conclusion seems surprising since in all studies of the synergic effect there is an increase in extraction, implying a higher distribution ratio in favour of the organic phase and pointing to higher $\underline{R}_f$ values: the decreased hydrophilicity more than compensates for the increased molar mass. Clearly there is still room for further investigations in the field of the chromatography of coordination compounds.

In all chromatographic work we are concerned with the partition of a solute between two phases and this phenomenon is exploited in its most direct form in liquid-liquid extraction between two immiscible liquid phases. The properties of a coordination compound that favour its extraction from an aqueous into an organic phase are large size and low hydrophilicity. Any factor which will increase the former and decrease the latter will enhance the distribution coefficient. For example, unlike the bis-8-hydroxy-quinolinates of the divalent transition metals (and all the tris-complexes), magnesium and strontium form water-insoluble complexes, $M(Ox)_2 \cdot 2H_2O$, which do not extract into chloroform unless the coordinated water is replaced by excess of un-ionised oxine, as in $Sr(Ox)_2 \cdot 2HOx$ (Ref. 46); butylcellosolve can serve this function when extracting the magnesium complex (Ref. 47).

With dithizone (H_2Dz), manganese(II) only forms a weak complex which is extracted into an organic solvent only at a moderately high pH value where it is prone to oxidation. Displacement of the water by pyridine or other nitrogen base gives the extractable complex $Mn(HDz)_2py_2$ (Ref. 48). This phenomenon is clearly reminiscent of the synergic effect in the extraction of uranium(VI) from nitric acid where the addition of tributylphosphate (TBP), or even more effectively of tributylphosphine oxide (TBPO), increases the extraction of the bis-chelate $UO_2(TTA)_2$ by several orders of magnitude (Ref. 49). The same favourable features of increased bulk and reduced hydrophilicity are seen in Freiser's use of 1,10-phenan-throline (IX; R = H) to enhance the extraction of nickel bis-dithizonate as the adduct, $Ni(HDz)_2 \cdot phenan$ (Ref. 50). This procedure has an additional advantage in that it speeds up an otherwise extremely slow rate of extraction of nickel dithizonate alone. It seems possible that the slow reaction between $Ni(H_2O)_6^{2+}$ and H_2Dz (or its conjugate base) to give a square planar complex is replaced by one between the reagent and a nickel-phenanthroline complex from which some water has already been displaced - and where there is no change in octahedral coordination anyway.

In addition to the liquid-liquid extraction of formally uncharged metal chelates, coordination compounds play a dominant role in the extraction of ion-pairs. Only 25 years have elapsed since Tribalat first showed that tetraphenylarsonium perrhenate could be extracted into chloroform whereas the corresponding molybdate remained in the aqueous phase (Ref. 51). Other large uni-negative anions such as MnO_4^-, ClO_4^-, IO_4^-, etc. can be extracted and separated from the more easily aquated polyvalent MoO_4^{2-}, WO_4^{2-} and CrO_4^{2-}. The bulky, hydrophobic cation can also be $CH_3(C_6H_5)_3As^+$, $(C_6H_5)_3S^+$, $(C_6H_5)_2I^+$, $Fe(phenan)_3^{2+}$, or a large cation derived from a basic dye such as Rhodamine B which will extract coordinated halo-complexes such as $SbCl_6^-$, $TlCl_4^-$, $TlBr_4^-$, $GaCl_4^-$, SbI_4^-, $SbBr_6^-$, $FeCl_4^-$ $FeBr_4^-$, $AuCl_4^-$, $AuBr_4^-$ etc. The conjugate acids of malachite green, methyl violet and many other dye-stuffs behave similarly.

The most fruitful development in this field stemmed from the discovery by Smith and Page in 1948 that liquid long-chain amines such as dioctylamine were able to extract strong acids such as HCl, HNO_3 and H_2SO_4 quantitatively from aqueous solutions into chloroform or nitrobenzene (Ref. 54). It was

soon realised that the ammonium salts so produced could exchange their
anions for others and so behave in a manner formally analogous to the
familiar anion-exchange resins. Many "liquid anion-exchangers" are
commercially available. A typical example is Aliquat-336(Cl), a viscous
yellow liquid, basically methyltricaprylammonium chloride with 27-33
carbon atoms on the average ($\underline{M}_r$ 475), the alkyl groups consisting mainly
of octyl and decyl chains. Such compounds can be used to extract an
astonishing variety of anions varying from simple species such as the
halide ions, to oxyanions such as ClO_3^-, ClO_4^-, ReO_4^-, and complex anions
such as $ZnCl_4^{2-}$, $Co(SCN)_4^{2-}$, $UO_2(Ox)_3^{2-}$, or anionic species such as $MY^{\underline{n}-4}$
derived from a cation $M^{\underline{n}+}$ and EDTA ($Na_2H_2Y \cdot 2H_2O$) (Ref. 55), or the
strongly coloured complexes of metals with metallochromic indicators such
as Xylenol Orange. By treating Aliquat-336(Cl) with a concentrated
solution of Erdmann's salt, $(NH_4^+)[Co(NH_3)_2(NO_2)_4^-]$ the chloride ion is
replaced by the Erdmannate ion, thus affording a coloured liquid anion-
exchanger which lends itself to a variety of analytical determinations
(Ref. 56). As typical of the elegant separations that can be carried
out by the extraction of ion-pairs derived from liquid anion exchangers by a
xylene solution of a commercial tertiary amine (Alamine-336; R_3N),
uranium, plutonium and neptunium can be separated in the form of
$(R_3NH)_2(UO_2Cl_4)$, $(R_3NH)_2PuCl_6$ and $(R_3NH)_2NpO_2Cl_2$, by adjusting the
composition of the initial aqueous phase (HCl) and that of the various
strip solutions (Ref. 57). Very many metal complexes can be extracted in
this way into solvents such as methylisobutylketone which can then be
nebulized to provide the most advantageous route to their determination by
atomic absorption or fluorescence spectroscopy. Some interesting
observations have yet to be extended, explained, and interpreted. Thus,
among complex cyanides the order of increasing extraction is
$Au(CN)_2^- >> Ag(CN)_2^-$ (linear ions); $Hg(CN)_4^{2-} >> Cd(CN)_4^{2-} > Zn(CN)_4^{2-}$ (tetrahedral
ions); $Pt(CN)_4^{2-} > Pd(CN)_4^{2-} >> Ni(CN)_4^{2-}$ (square planar ions). Tetrahedral ions
are more strongly extracted than square planar ions of the same charge
(Ref. 56).

In forming bulky, extractable ion-pairs the possibilities of steric
hindrance to coordination must always be born in mind. Whereas 2,2-bi-
pyridyl (VIII; R = H), 1,10-phenanthroline (IX; R = H) and 2,2-bis(iso-
quinolyl) (X; R = H) will form stable complexes with all the $\underline{d}$-block,
divalent transition metal cations, M^{2+} (M = Mn^{2+} to Zn^{2+}), steric
hindrance prevents the formation of tris-complexes by homologues of these
ligands with methyl groups adjacent to the nitrogen atoms (VIII, IX and
X; R = CH_3). Steric hindrance to coordination is also shown by biquinolyl
(XI). Although none of these ligands will give extractable tris-complexes
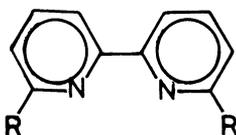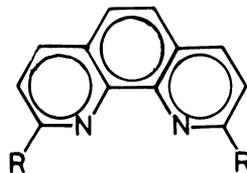
(VIII)   (IX)
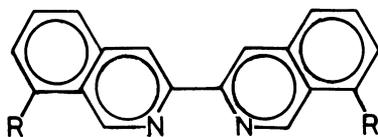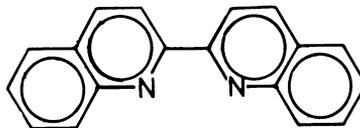
(X)   (XI)

with iron(II), they can all give extractable bis-complexes with copper(I) which, of course, employs $4s4p^3$ hybridised orbitals. The two ligands then lie in planes at right angles to each other and there is now no steric hindrance in the formation of the tetrahedrally coordinated complex in such an ion-pair as $Cu(biquin)_2^+Cl^-$. These circumstances lead to a most satisfying way for determining copper (as Cu(I)) in the presence of iron (as Fe(II))(Ref. 13). The low results at one time obtained in determining traces of copper in stainless steels with this reagent has been shown to be due to the formation of an interesting coordination compound of chromium with citrate which is so constructed that it can also accommodate copper(II) stably (Ref. 56).

Yet another aspect of current coordination chemistry is well illustrated
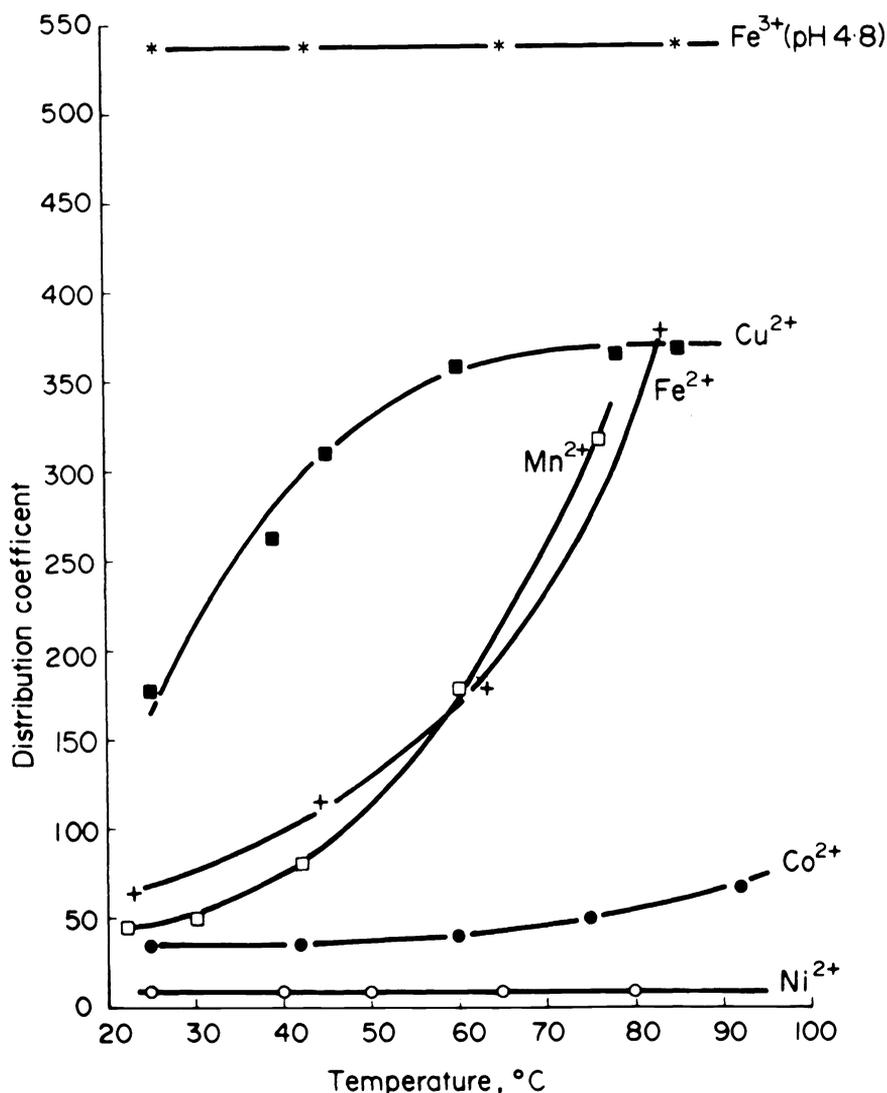
Fig. 2. The effect of temperature on the distribution coefficients of first row transition elements between equal volumes of an aqueous phase pH 5.0 - 5.2 and a 30% solution of sodium diethylhexylphosphate (NaDEHP) in a high b.p. hydrocarbon oil, Catenaz 11 (Ref. 59).

by the commercially important separation of Ni and Co(II) by extraction
with diethylhexylphosphoric acid (H.DEHP). Data for a variety of metals
are shown in Fig. 2.   The most striking feature is the increase in the
extraction of cobalt (but not that of nickel) with rise of temperature.
At the same time there is a change in colour as the pink octahedral
complex extracted at lower temperatures is replaced by the blue, and less
hydrophilic tetrahedral complex (Ref. 59).

The increase in entropy in the reaction

$$\text{Co(DEHP)}_2 \cdot 2H_2O \quad \underset{\text{cool}}{\overset{\text{heat}}{\rightleftharpoons}} \quad \text{Co(DEHP)}_2 \quad + \quad 2H_2O \qquad (5)$$

$$\text{pink, octahedral} \qquad\qquad\qquad \text{blue, tetrahedral}$$

displaces the equilibrium to the right with rising temperature and so
promotes the extraction of Co(II) into the organic phase. The major
factor working against the formation of tetrahedral complexes for all the
dipositive cations is the difference between the ligand-field stabilization
energy, $\Delta_{oct.} - \Delta_{tetr.} = 5/9 \Delta_{oct.}$. This amounts to 0.0 $\Delta_{oct.}$ for Mn(II),
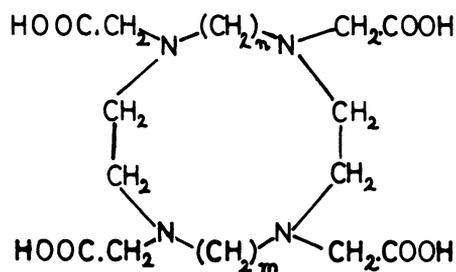0.133 $\Delta_{oct.}$ for Fe(II), 0.267 $\Delta_{oct.}$ for Co(II) and no less than 0.844 $\Delta_{oct.}$
for Ni(II).

Everyone will be aware of the dramatic developments in titrimetric
analysis consequent upon the introduction by G. Schwarzenbach of procedures
based on the formation of stable coordination compounds between metals
and a variety of aminopolycarboxylic acids of which ethylenedinitrile-
tetraacetic acid (XII; EDTA) is the best known (Ref. 60). Once it had
become clear that substances such as murexide and o-dihydroxyazodyestuffs
could serve as metallochromic indicators, and Schwarzenbach had demonstrated
how the requisite metal-bonding features could be incorporated into many
conventional acid-base indicators (to give e.g. a metalphthalein), a never
ending stream of new compounds have been prepared, some of which have
proved especially suitable for detecting the end-points in the titrations
of particular metals. The basic requirements are, of course, that
coordination to a metal should give a thermodynamically stable coordination
compound with a colour that contrasts with that of the uncoordinated
indicator and which has a lower formation constant than that of the complex
formed by the metal and the complexone used as the titrant (Ref. 60). A
great deal of work has been carried out to modify the structure of complex-
ones so as to give more stable complexes with particular metals, especially
with the alkali metals. Replacement of O by S, N by P, and attempts to
exploit steric hindrance in various ways have not met with much success.

The goal of achieving sufficiently high formation constants $(K_{ML} >> 10^7)$

for the titration of e.g. lithium has not been reached although EDTA (XII)
and uramildiacetic acid (XIII) and its homologues have shown the most
promise (Ref. 61).

The anomalous stability order for the formation constants of EDTA where

          (XII); EDTA   (XIII); Uramildiacetic acid

$K_{BaL} < K_{SrL} < K_{CaL} > K_{MgL}$ can be explained on steric grounds if it is assumed that
the ligand is sufficiently flexible when bonding through its two donor
nitrogen and four donor oxygen atoms to adapt its enclosure to ions of size
decreasing down from Ba^{2+} to Ca^{2+} whereas steric repulsion prevents a
closer approach sufficient to give strong binding to the much smaller
magnesium ion (cf. Table 5 for ionic radii). This situation has recently
been thrown open for further work by the preparation of a new series of
complexones based on nitrogen macrocycles, for Stetter and Frank (Ref. 62)

have now reported some quite dramatic results for the complexones XIV-XVI
(Table 3).

$$HOOC.CH_2-N-(CH_2)_n-N-CH_2COOH$$

(the cyclic structure diagram)

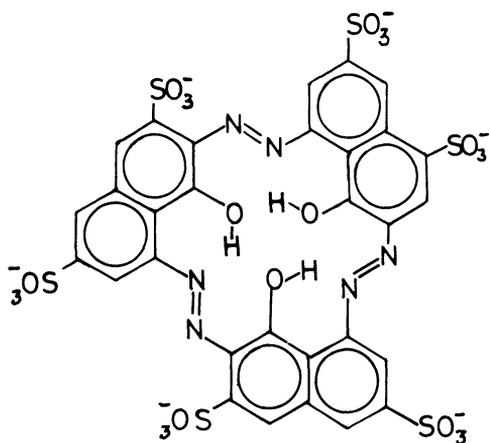|		
(XIV)	$\underline{n} = \underline{m} = 2$	
(XV)	$\underline{n} = 2, \underline{m} = 3$	
(XVI)	$\underline{n} = \underline{m} = 3$	

TABLE 3.   Stability constants, log $\underline{K}_{ML}$, of complexes of
               amino-polycarboxylic acids with alkaline earth
               cations. Valid for $20^{\circ}C$ and I = 0.1M(KCl)(Ref. 62)

Ion	(XIV)	(XV)	(XVI)	EDTA	CDTA
Mg^{2+}	11.03	6.36	3.02	9.12	10.32
$\Delta_{Ca,Mg}$	+ 4.82	+ 1.70	+ 6.46	+ 1.88	+ 2.18
Ca^{2+}	15.85	8.06	9.48	11.00	12.50
$\Delta_{Sr,Ca}$	- 3.05	+ 3.64	- 3.33	- 2.20	- 2.50
Sr^{2+}	12.80	11.70	6.15	8.80	10.00

$\Delta_{Ca,Mg}$ =log $\underline{K}_{CaL}$ - log $\underline{K}_{MgL}$; $\Delta_{Sr,Ca}$ = log $\underline{K}_{SrL}$ - log $\underline{K}_{CaL}$;

EDTA = ethylenedinitriletetraaxetic acid (XII);
CDTA = cyclohexanediaminetetraacetic acid.

With complexones XIV and XVI the stability of the calcium complex relative
to the magnesium complex is far greater than for EDTA, and with (XV) there
is a remarkable perference for strontium relative to calcium, reversing
the trend found in all earlier work. Clearly, the aspect of compromise
between the size of the enclosure permitted by steric repulsion between
the component atoms of the complexone and the size of the encapsulated
cation must depend strongly and even critically on the structure and
flexibility of the ligand.

An early example of a coordination compound capable of enclosing a cation
of preferred, favourable ionic radius is provided by the macrocyclic
azodyestuff (XVII) prepared by Close and West in 1960. This was described
as a specific indicator for calcium (Ref. 63). Up to 1967 the literature
on macrocyclic ethers (as XVIII) was limited and the possibility of their
being complexing agents was not realised until Petersen obtained the first
crown ether (dibenzo-18-crown-6; XIX, $\underline{n} = \underline{m} = 2$) as an unexpected by-product
insoluble in methanol but readily soluble on the addition of sodium salts.
The naturally occuring macrocyclic antibiotics valinomvcin and nonactin
were known to exert interesting biological effects related to their
ability to transport Na^{+} and K^{+} across cell membranes and were subsequently
shown to exhibit a marked preference for the coordination of potassium
(or rubidium) ions as against sodium ions. The potentialities of such
compounds as models of biological systems, for selective ion electrodes,
for conducting analyses and reactions in organic solvents, and as specific
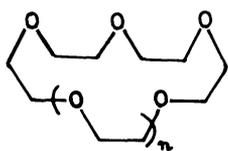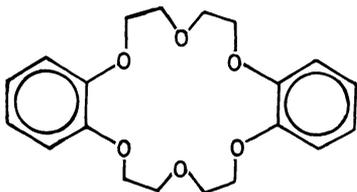
(XVII)

complexing agents has stimulated an enormous amount of work (Refs. 64 - 69) which has, unfortunately, seldom been directed towards purely analytical applications, but see Note a.

The size of the cavity and the nature of the donor atoms influence the nature of the cations that are trapped preferentially within such macrocycles and also the overall complex stability, although, of course, the nature of the counter ion and the infl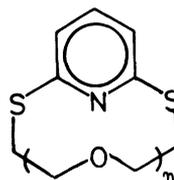uence of the solvent used must also be considered. Dibenzo-18-crown-6 (XIX; $\underline{n} = \underline{m} = 2$ will solubilize potassium permanganate in a solvent such as dichloromethane or benzene. The macrocycles (XX; $\underline{n} = 2$ or 3) will solubilize $NaMnO_4$ instantaneously, but not $KMnO_4$, or lithium, rubidium, rubidium, caesium, ammonium or silver salts (Ref. 66). An enormous number of compounds analogous to (XVIII), (XIX) and (XX) have been synthesized and examined for their metal-complexing properties but a different

(XVIII)   (XIX)   (XX)

approach has been to synthesize 'host' molecules containing rigid binaphthyl units where the two naphthalene rings occupy different planes, each perpendicular to the best plane of the cyclic ether (Ref. 67). A solution of the compound (XXI) in dry THF at -80°C will dissolve potassium metal to give a green reducing solution in which the potassium ion, K^+, is encapsulated by the ring of oxygen atoms and its electron is de-localized in the aromatic system. With compound (XXII; R = morpholino), the cavity is about 2.4 - 3.1 Å in diameter and can give a formally neutral complex when a potassium ion becomes the 'guest'. This formally neutral species is soluble in water as well as in organic solvents and is stable to acids.

Note a: In a paper presented in Section IV of the present Conference, K. Ueno et al. have synthesized [4'-(picrylamino)-benzo]-15-crown-5 (HA) as a new coloured reagent for potassium [74]. The orange compound is almost insoluble in water but easily soluble in organic solvents (λ_{max} 390 nm in $CHCl_3$) and gives an extractable blood-red potassium complex (KA·HA; λ_{max} 460 nm). The absorbance at 560 nm is linearly proportional to the concentration of potassium up to 300 ppm. The dis-appointingly low distribution ratio, $[K^+]org/[K^+]aq = 0.017$ can probably be attributed to the presence of very hydrophilic nitro groups.
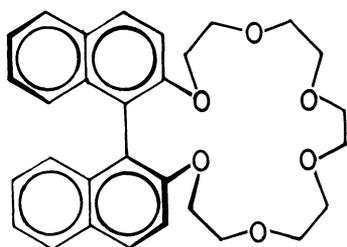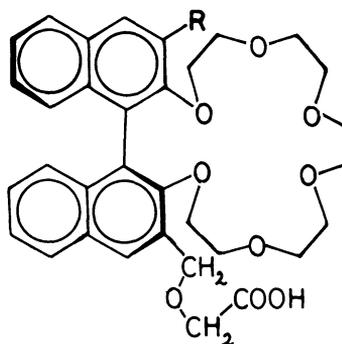
(XXI)   (XXII)

With Ba^{2+} two molecules of (XXII; R = morpholino) react to give a molecular sandwich in which the barium ion is, in a manner of speaking, completely enveloped in a lipophilic skin, its double positive charge being neutralised by the two carboxylate ions. The complex is soluble in organic solvents, stable to chromatography, and does not give a precipitate of barium sulphate when sulphuric acid is added to its solution. If two carboxylate arms are provided (as XXII; R = $-CH_2.O.CH_2.COOH$) a stable complex with Sr^{2+} results and the complex was, in fact, prepared by scavenging strontium ions from a bulk sample of barium hydroxide. A Ba^{2+} ion (radius 1.49 Å) does not fit in so well as Sr^{2+} (Ref. 67). Many thermodynamic studies have been carried out on the kinetics of complex formation and the stabilities of the various metal complexes (Ref. 68).

A second type of complexing agent is provided by the bicyclic macrocycles (XXIII, a - f) usually referred to as cryptates (Refs. 64 - 69). Analogous compounds with sulphur replacing some of the oxygen atoms have also been prepared.
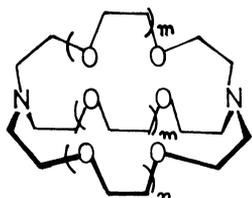
	m	n
(a)	0	1
(b)	1	0
(c)	1	1
(d)	1	2
(e)	2	1
(f)	2	2
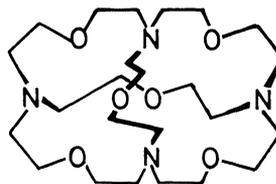
(XXIII)   (XXIV)

The stability of a complex is a compromise between the free energy of solvation and the free energy of complex formation. The selectivity of a ligand for a particular cation will depend on the way in which the free energy of complexation varies with respect to the free energy of the solvated ion. Now ΔG(solvation) increases monotonically as the radius of the cation decreases along a series (Table 5). Much the same order would be expected for ΔG(complexation) by a polydentate ligand provided it were able to adjust to all cation sizes. If, however, the cavity is of a fixed dimension, ΔG(complexation) will increase as the size of the cation decreases until it reaches this limiting size of the cavity. For smaller ions, ΔG(complexation) cannot increase further since the cavity cannot get smaller and maintain contact between the guest cation and the bonding sites of the host ligand. These points are illustrated in Tables 4 and 5 in which the favoured ion for a particular cryptate is underlined. All stabilities are found to be much higher in methanol than in water; for stabilities increase as the dielectric constant decreases. This also increases the selectivity by favouring (i) the most stable complexes, and (ii) larger ions relative to smaller ions. Since oxygen sites have a higher polarity but a lower polarizability than nitrogen sites, alkali

cations are more strongly solvated by O than by N, whereas Tl[+] and Ag^{+} interact more strongly with nitrogen sites. No ligand has yet been

TABLE 4.   Stability constants of cryptates. Data for water at 25°C (Ref. 69).

Cryptate (XXIII)		Li^+	Na^+	K^+	Rb^+	Cs^+	Mg^{2+}	Ca^{2+}	Sr^{2+}	Ba^{2+}
m	n									
(a) 0	1	5.5	3.2	<2.0	<2.0	<2.0	2.5	2.5	<2.0	2.0
(b) 1	0	2.50	5.40	3.95	2.55	<2.0	<2.0	6.95	7.35	6.30
(c) 1	1	<2.0	3.9	5.4	4.35	<2.0	<2.0	4.4	8.0	9.5
(d) 1	2	<2.0	1.65	2.2	2.05	2.0	<2.0	~2.0	3.4	6.0
(e) 2	1	<2.0	<2.0	<2.0	<0.7	<2.0	<2.0	~2.0	~2.0	3.65
(f) 2	2	<2.0	<2.0	<2.0	<0.5	<2.0	<2.0	<2.0	<2.0	-
EDTA (XII)		2.85	1.78	0.96	0.58	0.15	9.12	11.0	8.80	7.78
(XIII)		5.61	3.33	1.94	-	-	8.19	8.31	6.93	6.13
Enniatin*		1.28	2.38	2.92	2.74	2.34	1.20	2.95	2.65	2.93
Valinomycin*		<0.7	0.67	4.90	5.26	4.41	0.7	2.70	2.23	3.34

*These data refer to measurements in methanol. In this solvent all stability constants are much higher than in water.

TABLE 5.   Data for cryptates (XXIII a - e) and dibenzocrown-6 (Ref. 69).

Cation	Li^+	Na^+	K^+	Rb^+	Cs^+	Mg^{2+}	Ca^{2+}	Sr^{2+}	Ba^{2+}
Ionic radius in Å	0.78	0.98	1.33	1.49	1.65	0.78	1.06	1.27	1.43
Hydration number	6	6	6	6	6	6	8	8	8
$-\Delta G^o$ (hydration), kcal mol^{-1}	-1,122	98.5	80.5	75.5	68.0	454	379	340	314
ligand	a	b	c	d	e	f	g		
cavity radius, Å	0.8	1.1	1.4	1.8	2.1	2.4			
number of binding sites	6	7	8	9	10	11			

g is dibenzocrown-6

found which shows a special selectivity for Rb^{+}. The cryptate (XXIII (c)) is quite exceptional in showing a high selectivity for Sr^{2+} (or Ba^{2+}) over Ca^{2+} and has been tested in decorporation experiments (Ref. 69).

By producing a cross-bridge as in the macrotricyclic cryptate (XXIV), a molecule with an almost spherical cavity of radius 1.8 Å is obtained as

cubic crystals, m.p. 196 - 200°C, resulting from a 12-stage synthesis (overall yield ∿2%). It dissolves caesium bromide and probably yields the strongest caesium complex yet made (log $\underline{K}$ = 3.4 in water). As might be expected, the reaction is slow (Ref. 70). Kinetics of the reactions between Ca^{2+} and cryptates have been studied and shed light on the conformational changes (exo-exo → exo-endo → endo-endo) in these ligands that must preceed complexation, and on the extent to which water of solvation persists in the transition state (Ref. 71). Such studies are, of course, highly relevant to the analytical uses of this type of complexing agent.

While a clear understanding of basic principles and requirements is leading to the controlled design and synthesis of tailor-made 'host' molecules for particular 'guest' ions, the analyst has reason to be grateful and cannot afford to overlook any opportunities provided by the unpredictable vagaries of crystal structures. For example, while hydrochloric acid is normally able to liberate a carboxylic acid from its potassium salt

$$R.CCOK \; + \; HCl \; \longrightarrow \; KCl \; + \; R.COOH \qquad\qquad\qquad (6)$$

exactly the opposite reaction takes place with catecholdiacetic acid ($\underline{o}$-$C_6H_4(OCH_2.COOH)_2$; H_2CDA) which reacts with an aqueous solution of potassium chloride to yield an insoluble coordination compound of potassium with the concomitant liberation of hydrochloric acid, thus :

$$2 \; H_2CDA \; + \; KCl \; \longrightarrow \; KHCDA.H_2CDA \; + \; HCl \qquad\qquad (7)$$

A sandwich of two molecules of H_2CDA provides 8 of the 10 oxygen atoms which encapsulate the potassium ion, the remaining coordination sphere being made up by an oxygen atom from each of two other molecules. It is stated that Li^+, Na^+, NH_4^+ and Cs^+ do not react in a similar fashion (Ref. 72).

Time does not permit of any detailed analysis of the factors which affect the colour (or fluorescence) of the great range of coordination compounds employed in absorptiometry (or fluorimetry) (Ref. 52). To take one specific example, the absorptiometric determination of iron(II) has led to the introduction of a series of reagents yielding tris-complexes of increasing linear absorption coefficients, e.g. 2,2-bipyridyl (ε = 7,930), 1,10-phenanthroline (ε = 11,100), 4,7-diphenyl-1,10-phenanthroline (ε = 22,140), 2.4.6-(2-pyridyl)-1,3,5-triazine (ε = 22,600) and the water-soluble 'ferrozine', 3-(2-pyridyl)-5,5-bis(4-sulphophenyl)-1,2,4-triazine (ε = 27,900). Although the cost of ferrozine is only about half that of 1,10-phenanthroline, the large quantities used in a continuous automatic analyser can raise an economic problem. This has recently been solved by realising that after measuring the absorption due to the tris-complex of iron(II), the sample can be subjected to mild oxidation which will generate the thermodynamically weaker tris-complex of iron(III) from which the iron can be removed by complexation with oxalate at 95°C, thus regenerating the ligand which is not attached itslef under these experimental conditions. This solution to a difficult problem in coordination chemistry demanded a careful appraisal of the thermodynamic stabilities of all possible components and a study of the kinetics of all the relevant reactions (Ref. 74).

We must conclude that stereochemical factors, reaction kinetics, conformational changes and ligand field stabilisation energies are all relevant to the uses of coordination compounds in analytical chemistry. Selectivity may be achieved by design or by a lucky chance; for there seems, at present, no way of predicting when some new coordination compound will turn up which owes its potential usefulness to an unexpected and unpredictable crystal structure.

BIBLIOGRAPHY

1. O. Brunck, Z. angew. Chem. 20, 1844 (1907); cf. L. Tschugaeff,
   Ber. 38, 2520 (1905).
2. R.G. Charles and H. Freiser, Anal. Chim. Acta 11, 101 (1954).
3. R.E. Rundle and L.E. Godycki, Acta Cryst. 6, 487 (1953):
   R.E. Rundle, J. Phys. Chem. 61, 45 (1957).
4. E. Frasson, R. Bardi and S. Bezzi, Acta Cryst. 12, 201 (1959).
5. F. Feigl, Chemistry of Specific Selective and Sensitive Reactions,
   Academic Press, New York (1949); Spot Tests in Inorganic Analysis,
   Elsevier Publishing Co., Amsterdam (1958)
6. D.G. O'Sullivan and P.W. Sadler, Analyst 82, 835 (1957).
7. F.J. Welcher, Organic Analytical Reagents, Van Nostrand, New York
   4 vols. (1947-1948).
8. J. Starý, The Solvent Extraction of Metal Chelates, Pergamon
   Press (1964).
9. A.K. De, S.M. Khopkar and R.A. Chalmers, Solvent Extraction of
   Metal Chelates, Van Nostrand, London (1970).
10. H. Diehl, Analytical Applications of the Dioximes, G.F. Smith
    Chemical Co., Columbus (Ohio) USA (1940).
11. H. Irving, E.J. Butler and M.F. Ring, J. Chem. Soc. 1489 (1949).
12. H. Irving and D.J. Clifton, J. Chem. Soc. 288 (1959).
13. H. Irving and L.D. Pettit, Analytical Chemistry (Proc. Feigl
    Symposium, Birmingham) 122 (1962), and refs. therein.
14. H. Irving and H.S. Rossotti, J. Chem. Soc. 2910 (1954);
    H. Irving and P. Massey-Beresford, unpublished results.
15. H. Irving, Zeit. Anal. Chem. 263, 264 (1973) and refs. therein.
16. H. Irving, Cronache Chim. 46 (1945).
17. B.M. Vanderborght and R.E. Van Grieken, Anal. Chem. 49, 311 (1977).
18. K.V. Krishnamurty and M.M. Reddy, Anal. Chem. 49, 222 (1977).
19. T. Braun and A.B. Farag, Anal. Chim. Acta 73, 301 (1974);
    Talanta 22, 699 (1975).
20. G.P. Baxter and R.C. Griffin, J. Amer. Chem. Soc. 34, 204 (1905).
21 J. van R. Smit, W. Robb and J.J. Jacobs, J. Inorg. Nuclear Chem.
    12, 95 (1959); 26, 509 (1964), and refs. therein.
    Cf. C.B. Amphlett, Inorganic Ion Exchangers, Elsevier, (1964).
22. J. van R. Smit, W. Robb and J.J. Jacobs, Nucleonics 17, 116 (1959).
23. R.J. Everett and H.A. Mottola, Anal. Chim. Acta 54, 309 (1971).
24. J. Stejskal, J. Soukup, J. Dolezal and V. Kourim, J. Radioanal. Chem.
    21, 371 (1974).
25. J. Dolezak, K. Stejskal, M. Tympl and V. Kourim, J. Radioanal. Chem.
    21, 381 (1974).
26. J. Krtil, J. Inorg. Nuclear Chem. 19, 298 (1961), and refs. therein.
27. M. Quereshi and R.C. Kaushik, Anal. Chem. 49, 165 (1977).
28. H.M.N.H. Irving, J. Radioanal. Chem. 33, 287 (1976).
29. M. Fedoroff, L. Debove and Ch. Loos-Neskovic, J. Radioanal. Chem.
    21, 331 (1974).
30. H.M.N.H. Irving, Analytical Sciences Monographs, No. 5, Chem. Soc.,
    London (1977).
31. K.J. Eisentraut, D.J. Grant and R.E. Sievers, Anal. Chem. 43, 2003
    (1971).
32. R. Belcher, Zeit. Anal. Chem. 263, 259 (1973).
33. E. Bayer, H.P. Müller and R. Sievers, Anal. Chem. 43, 2012 (1971).
34. T.J. Cardwell, D.J. Desarro and P.C. Uden, Anal. Chim. Acta 85,
    415 (1976), and refs. therein.
35. P.C. Uden and F.H. Walkers, Anal. Chim. Acta 79, 175 (1975).
36. E.H. Daughtrey, A.W. Fitchett and P. Muslak, Anal. Chim. Acta 79,
    199 (1975).
37. J. Delventhal, H. Keck and W. Kuchen, Angew. Chem. 84, 485, 832
    (1972).
38. J.J. Franken, C. Vidal-Madjar and G. Guiochon, Anal. Chem. 43,
    2034 (1971).
39. B.W. Bradford, D. Harvey and D.E. Chalkley, J. Inst. Petrol (London)
    41, 80 (1955); cf. D.L. Schmitt and H.B. Jonassen, Anal. Chim. Acta
    49, 580 (1970).
40. E. Gil-Av and V. Schurig, Anal. Chem. 43, 2030 (1971).
41. G. Iwantscheff, Das Dithizon und seine anwendung in der Mikro- und
    Spurenanalyse, Verlag Chemie, Weinheim (1972), and refs. therein.
42. W. Lautenschlager, S. Pahlik and G. Tölg, Zeit. Anal. Chem. 260,
    203 (1972).
43. E. Ludvig, R. Morgenstern and U. Uhlemann, Anal. Chim. Acta 86,
    157 (1976).

44. M. Yamamoto and Y. Yamamoto, _Anal. Chim. Acta_ 87, 375 (1977).
45. R.H. Oksala and R.A. Krause, _Anal. Chim. Acta_ 85, 351 (1976).
46. D. Dyrssen, _Svensk Kem. Tidskr._ 67, 311 (1955).
47. C.L. Luke and M.E. Campbell, _Anal. Chem._ 26, 1778 (1954); 28, 1443 (1956).
48. Z. Marzenko and M. Mojski, _Chim. analyt._ (Paris) 53, 529 (1971); _Analyt. Chim. Acta_ 54, 469 (1971).
49. H.M.N.H. Irving, Synergism in the Solvent Extraction of Metal Chelates, in _Solvent Extraction Chemistry_, Ed. D. Dyrssen, J.O. Liljenzin and J. Rydberg, North-Holland, Amsterdam (1967).
50. K.S. Math and H. Freiser, _Anal. Chem._ 41, 1682 (1969); _Chem. Commun._ 110 (1970).
51. S. Tribalat, _Anal. Chim. Acta_ 3, 113 (1949); 4, 228 (1950).
52. E.B. Sandell, _Colorimetric Determination of Traces of Metals_, Interscience, New York, London (1959).
53. E.B. Sandell and H. Onishi, _Anal. Chim. Acta_ 11, 444 (1954); 13, 159 (1955).
54. E.L. Smith and J.E. Page, _J. Soc. Chem. Ind._ 67, 48 (1948).
55. H.M.N.H. Irving and R.H. Al-Jarrah, _Anal. Chim. Acta_ 74, 321 (1975).
56. H.M.N.H. Irving and A.D. Damodaran, _Anal. Chim. Acta_ 53, 267 (1971).
57. J.C. Veselsky, Pak Chan Kirl and N. Sezginer, _J. Radioanal. Chem._ 21, 97 (1974).
58. H.M.N.H. Irving and W.R. Tomlinson, _Talanta_ 15, 1267 (1968).
59. J.E. Barnes, J.H. Setchfield and G.O.R. Williams, _J. Inorg. Nuclear Chem._ 38, 1065 (1976).
60. G. Schwarzenbach and H. Flaschka, _Complexometric Titrations_, Second English Edition trans. and revised by H.M.N.H. Irving, Methuen and Co., London (1969).
61. H. Irving and J.J.R.F. da Silva, _J. Chem. Soc._ 448, 458 (1963).
62. H. Stetter and W. Frank, _Angew. Chem. Internat._ Ed. 88, 760 (1976).
63. R.A. Close and T.S. West, _Talanta_ 5, 221 (1960).
64. C.J. Pedersen and H.H. Frensdorff, _Angew. Chem. Internat._ Ed. 11, 16 (1972) and refs. therein.
65. J.J. Christensen, J.O. Hill and R.M. Izatt, _Science_ 174, 459 (1971).
66. F. Vögtle and E. Weber, _Angew. Chem. Internat._ Ed. 13, 149 (1974).
67. D.J. Cram and J.M. Cram, _Science_ 183, 803 (1974) and refs. therein.
68. R.M. Izatt, R.E. Terry, B.L. Haymore, L.D. Hanesn, N.K. Dalley, A.G. Avondit and J.J. Christensen, _J. Amer. Chem. Soc._ 98, 7620 (1976).
69. J.M. Lehn and J.P. Savage, _J. Amer. Chem. Soc._ 97, 6700 (1975).
70. E. Graf and Jean-Marie Lehn, _J. Amer. Chem. Soc._ 97, 5022 (1975).
71. V.M. Loyola, R.G. Wilkins and R. Pizer, _J. Amer. Chem. Soc._ 97, 7383 (1975).
72. E.A. Grewen, W.L. Duax, G.M. Smith and F. Wudl, _J. Amer. Chem. Soc._ 97, 6689 (1975).
73. V.V.S. Eswara Dutt and H.A. Mottola, _Anal. Chem._ 49, 319 (1977).
74. M. Takagi, H. Nakamura and K. Ueno, Paper IV in _Proc. XVIII Int. Conference on Coordination Chemistry_, São Paulo, Brazil (1977).