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High-performance liquid chromatographic study of ligand-exchange reactions of fluorinated metal β-diketone chelates

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ABSTRACT

Ligand redistribution reactions among gallium, indium, copper and nickel fluorinated β-diketonates were investigated by normal-phase high-performance liquid chromatography on a silica column. Reactions taking place at ambient temperature in tetrahydrofuran–heptane solutions were shown to proceed with statistical ligand exchange. Good chromatographic characteristics were seen for the range of initial and product gallium chelates. Although other complexes were not eluted under the conditions used, the reactions which occurred in mixed-metal systems could be inferred from examination of gallium chelate chromatograms.

INTRODUCTION

Gas chromatographic (GC) separation of neutral metal chelates is limited by requirements of adequate volatility and thermal stability[1]. High-performance liquid chromatography (HPLC), however, allows appplication to metal chelates that are less volatile or thermally stable, and provides selectivity through suitable choice of stationary and mobile phases.

HPLC of metal complexes was first reported by Huber and Kraak[2] who employed liquid–liquid partition chromatography in a ternary solvent system, consisting of water, ethanol and 2,2,4-trimethylpentane. They established conditions necessary to separate as many as six metal acetylacetonates, among them those of Be(II), Al(III), Cr(III), Fe(III), Co(III), NI(II), Cu(II), Zn(II), Zr(IV) and Ru(III). Reports in which high-performance bonded phase or liquid–solid chromatography have been applied to metal complexes have included separations of metal chelates of tetradentate β-ketoamines[3–6], metal β-diketonates[6–9], metal cluster complexes[10], organoiron complexes[11], Rh and Ir triphenylphosphine complexes[12], metal 8-hydroxyquinoline complexes[13,14], dialkyldithiocarbamates[15,16] and crown ether complexes[17]. Review papers have further detailed the research on this subject[18,19].

In addition to the application to the separation of non-volatile and thermally unstable metal chelates, HPLC can be used to study their reactions, such as ligand

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exchange between two metal chelates with different ligands. A study of ligand-exchange reactions between fluorinated gallium, indium and aluminum β-diketonate chelates has been reported by GC with microwave-induced plasma (MIP) detection[20]. However, there is the possbility that the ligand-exchange reactions did not occur in the solution, but took place at least in part, in the gaseous phase in the heated injection port of the gas chromatograph. To investigate and confirm that the ligand-exchange reactions did occur in the liquid phase, the use of HPLC was necessary.

No HPLC study of ligand-exchange reactions of fluorinated gallium β-diketonates has previously been reported. In our study, a normal-phase separation mode was used to investigate these reactions between fluorinated gallium, indium, copper and nickel β-diketonates, and to prove that they did occur in the liquid phase. The ligands tested were 1,1,1-trifluoropentane-2,4-dione (HTFA), 1,1,1-trifluoro-hexane-2,4-dione (HTFEA), 1,1,1-trifluoro-5,5-dimethylhexane-2,4-dione (HTTB) and 1,1,1-trifluoro-6-methylheptane-2,4-dione (HTIB).

EXPERIMENTAL

Instrumentation

A HPLC system (Perkin-Elmer, Norwalk, CT, U.S.A.), equipped with a Series 100 pump and a TriDet detector was employed. The mobile phase was tetrahydrofuran–heptane (specific compositions of the mobile phase are listed in Table I and in the chromatograms). UV detection was at 254 nm. The column was a Spherisorb S5W silica column (5 μm, 150 × 4.6 mm I.D.) (Keystone Scientific, Bellefonte, PA, U.S.A.). A 10-μl sample loop was used and chromatograms were recorded on an Omniscribe recorder (Houston Instruments, Austin, TX, U.S.A.).

Materials and procedures

The procedures for the preparation of $Ga(TFA)_3$ and $In(TFA)_3$ have been described[20]. $Ga(TFEA)_3$, $Ga(TTB)_3$ and $Ga(TIB)_3$ were prepared in a similar way to that for $Ga(TFA)_3$. A procedure similar to that given by Berg and Truemper[21] was used to prepare $Cu(TFA)_2$ and $Ni(TFA)_2$. This involved shaking an alcoholic solution of the ligand with a 5% nitrate solution of the corresponding metal, buffered

TABLE I

CONDITIONS OF LIGAND-EXCHANGE REACTIONS STUDIED WITH HPLC

Temperature was 25°C.

Initial chelates	*Molar ratio*	*Solvent (THF–heptane, v/v)*	*Reaction time (h)*
$Ga(TFA)_3/Ga(TIB)_3$	3:2	15:85	24
$Ga(TFA)_3/Ga(TFEA)_3$	1:1	15:85	24
$Ga(TTB)_3/Ga(TFEA)_3/Ga(TFA)_3$	7:10:14	7.5:92.5	28
$Ga(TIB)_3/In(TFA)_3$	0.5:1	13:87	330
$Ga(TTB)_3/Cu(TFA)_2$	2:5	14:86	24
$Ga(TFA)_3/Cu(TTB)_2$	1:1	15:85	16
$Ga(TTB)_3/Ni(TFA)_2$	0.5:1	13:87	330

with sodium acetate (5 g for every 100 ml of solution). After precipitation, the chelate was collected by filtration, air-dried, recrystallized from benzene, and air-dried again.

Ligand-exchange reactions were carried out by dissolving the initial metal chelates in a portion of the mobile phase and allowing the reactions to take place under the conditions described in Table I. These conditions were such that no further changes in the chromatograms obtained were observed for longer reaction times. Since the chelates were difficult to dissolve directly in the mobile phase, they were first dissolved in tetrahydrofuran (THF) and then diluted with heptane to bring the solvent compositions to those of the mobile phases employed in HPLC. The concentrations of the chelates in these solutions of reaction mixtures were in the mmol/l range. The reaction mixtures were analyzed after the time periods specified in Table I.

RESULTS AND DISCUSSION

Ligand-exchange reaction between two gallium chelates

$Ga(TFA)_3$ and $Ga(TIB)_3$ undergo ligand exchange. The equilibrium process may be described as follows:

$$Ga(TFA)_3 + Ga(TIB)_3 \rightleftharpoons Ga(TFA)_2(TIB) + Ga(TFA)(TIB)_2$$

After the reaction procedure described in Table I was carried out, the reaction mixture was chromatographed. Fig. 1 shows the separation of four resultant gallium chelates under the experimental conditions indicated. THF–heptane (3:17, v/v) proved to be a suitable mobile phase for baseline separation and good peak shape with elution in < 4 min. Peaks 1 and 4 were identified as $Ga(TIB)_3$ and $Ga(TFA)_3$, respectively, by retention-time comparison with pure chelates. Peaks 2 and 3, eluted between peaks 1 and 4, were identified as $Ga(TIB)_2(TFA)$ and $Ga(TIB)(TFA)_2$. Since a normal-phase mode was employed, chelate species with ligands of greater carbon number and molecular weight tended to be eluted earlier; the elution order of $Ga(TIB)_3 < Ga(TIB)_2(TFA) < Ga(TIB)(TFA)_2 < Ga(TFA)_3$ showed this trend. The redistribution had clearly occurred during the 24-h liquid-phase reaction; the good resolution and peak shapes obtained indicated that no discernable further redistribution occurred during the chromatographic elution process.

Ligand-exchange reaction between $Ga(TFA)_3$ and $Ga(TFEA)_3$ was then carried out under similar conditions. Fig. 2 illustrates the separation of the resulting mixture. The sequence of the peaks, based on retention-time comparison with pure chelates, was in an order similar to that in the previous redistribution reaction, and liquid-phase reaction at room temperature had certainly taken place. Again, excellent peak shape and resolution indicated no discernable on-column redistribution.

Ligand-exchange reaction among three gallium chelates

A ligand-exchange reaction between $Ga(TTB)_3$, $Ga(TFEA)_3$ and $Ga(TFA)_3$ was then carried out to serve as an example of a triple exchange among three different chelates. Following the procedure listed in Table I, the chromatogram shown in Fig. 3 was obtained with seven baseline-separated peaks. Identifications of these peaks were made by comparing retention times with those of the products obtained separately from ligand-exchange reactions between $Ga(TTB)_3$ and $Ga(TFA)_3$, between

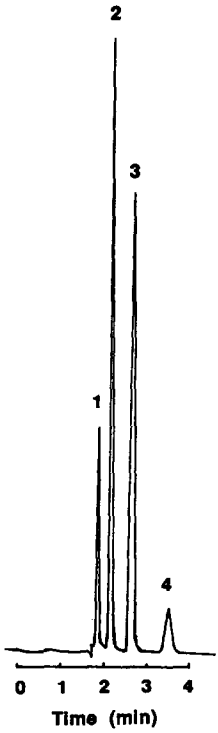
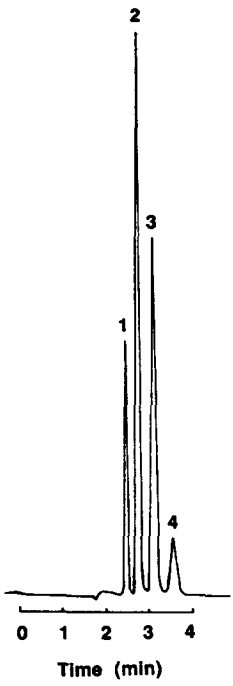


Fig. 1. HPLC separation of mixture of ligand-exchange reaction products formed from $Ga(TFA)_3$ and $Ga(TIB)_3$. Column 5 μm silica, 150 × 4.6 mm I.D.; mobile phase THF–heptane (3:17, v/v); flow-rate 1.0 ml/min; UV detection 254 nm; reaction time 24 h at 25°C. Peaks: 1 = $Ga(TIB)_3$; 2 = $Ga(TFA)(TIB)_2$; 3 = $Ga(TFA)_2(TIB)$; 4 = $Ga(TFA)_3$.

$Ga(TTB)_3$ and $Ga(TFEA)_3$, and between $Ga(TFEA)_3$ and $Ga(TFA)_3$. Peaks 3, 4 and 5 are each considered to consists of two unresolved gallium chelates. An interesting observation is that peak 3 consists of Ga(TTB)(TFEA)$_2$ and Ga(TTB)(TTB)(TFA), the underlined parts of the two chelates being designated to show the difference between them. Since the two chelates had virtually identical retention, the two chelated ligands (TFEA)$_2$ contribute the same overall retention as the two chelated ligands (TTB)(TFA) present together. A similar effect is also noted in peak 5, which consists of Ga(TTB)(TFA)(TFA) and Ga(TFEA)$_2$(TFA). Again the underlined parts (TFEA)$_2$ and (TTB)(TFA) show the only difference between these two similarly retained chelates.

The complex which contained three different ligands, Ga(TTB)(TFEA)(TFA), was expected to be produced from the ligand-exchange reaction among the three chelates, $Ga(TTB)_3$, $Ga(TFEA)_3$ and $Ga(TFA)_3$. However, since it could not be produced by ligand-redistribution reactions between any two of these three chelates only, its direct identification, by retention-time comparison with such reaction products, was impossible. Therefore, retention of Ga(TTB)(TFEA)(TFA) was deduced by arguments similar to those for peaks 3 and 5. Since the only difference between



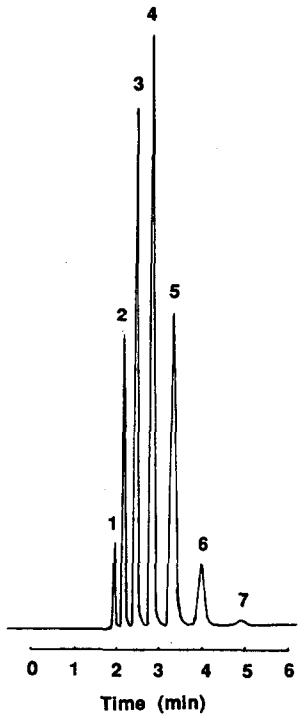


Fig. 2. HPLC separation of mixture of ligand-exchange reaction products formed from $Ga(TFA)_3$ and $Ga(TFEA)_3$. Conditions as in Fig. 1. Peaks: 1 = $Ga(TFEA)_3$; 2 = $Ga(TFA)(TFEA)_2$; 3 = $Ga(TFA)_2(TFEA)$; 4 = $Ga(TFA)_3$.

Fig. 3. HPLC separation of mixture of ligand-exchange reaction products formed from $Ga(TTB)_3$, $Ga(TFEA)_3$ and $Ga(TFA)_3$. Column 5 μm silica, 150 × 4.6 mm I.D.; mobile phase THF–heptane (7.5:92.5, v/v); flow-rate 1.0 ml/min; UV detection 254 nm; reaction time 28 h, at 25°C. Peaks: 1 = $GA(TTB)_3$; 2 = $Ga(TTB)_2(TFEA)$; 3 = $Ga(TTB)(TFEA)_2$ and $Ga(TTB)_2(TFA)$; 4 = $Ga(TFEA)_3$ and $Ga(TTB)(TFEA)(TFA)$; 5 = $Ga(TTB)(TFA)_2$ and $Ga(TFEA)_2(TFA)$; 6 = $Ga(TFEA)(TFA)_2$; 7 = $Ga(TFA)_3$.

$Ga(\underline{TFEA})_2(TFEA)$ and $Ga(\underline{TTB})(\underline{TFA})(TFEA)$ is that between the two underlined parts and since these were previously observed to give the same overall retention, peak 4 which was identified as containing $Ga(\underline{TFEA})_2(TFEA)$ [*i.e.* $Ga(TFEA)_3$], should also contain $Ga(\underline{TTB})(\underline{TFA})(TFEA)$ [which is $Ga(TTB)(TFEA)(TFA)$]. The magnitude of the response observed for peak 4 also indicated the presence of $Ga(TTB)(TFEA)(TFA)$ in addition to $Ga(TFEA)_3$; only a small peak would be expected for the latter as a result of the statistical nature of the redistribution reaction. In the reaction described, the molar ratio of $Ga(TTB)_3$, $Ga(TFEA)_3$ and $Ga(TFA)_3$ was chosen as 7:10:14, in order to present a clear redistribution chromatogram with peaks of significant scale for all species. However, for the equimolar case, the statistical response ratio, shown in parentheses (assuming identical molar absorptivities for all chelates at 254 nm), for peaks 1–7 (Fig. 3) would be predicted as peak 1 (1), peak 2 (3), peak 3 (3+3), peak 4 (9+1), peak 5 (3+3), peak 6 (3) and peak 7 (1). The lowest relative amounts of redistributed chelates are for the symmetrical complexes. Al-

though the experiment described gives skewed response data, the general trend is clearly shown as consistent with the foregoing analysis.

Ligand-exchange reactions between gallium and indium chelates

$Ga(TIB)_3$ and $In(TFA)_3$ were chosen to exemplify the HPLC study of ligand-exchange reactions between gallium and indium chelates. After allowing the two chelates to react according to the procedure listed in Table I, the reaction products were chromatographed (Fig. 4) to give four symmetrical baseline-resolved peaks. By comparing the retention times of the peaks with those obtained from ligand-exchange reaction between $Ga(TIB)_3$ and $Ga(TFA)_3$, peaks 1, 2, 3 and 4 were identified as $Ga(TIB)_3$,$Ga(TIB)_2(TFA)$, $Ga(TIB)(TFA)_2$ and $Ga(TFA)_3$, respectively. Although it has been shown by GC[20] that the mixture of ligand-exchange reaction products obtained from $Ga(TIB)^3$ and $In(TFA)_3$ did contain $In(TIB)_3$ and $In(TFA)_3$ in addition to the four gallium chelates, the indium chelates could not be eluted from the HPLC system under the conditions employed. However, the HPLC study proved that the ligand-exchange reactions between gallium and indium fluorinated β-diketone chelates did proceed in the liquid phase. Again there was no chromatographic evi-

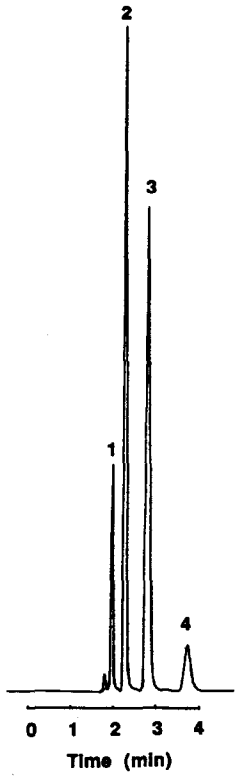


Fig. 4. HPLC separation of mixture of ligand-exchange reaction products formed from $Ga(TIB)_3$ and $In(TFA)_3$. Column 5 μm silica, 150 × 4.6 mm I.D.; mobile phase THF–heptane (13:87, v/v); flow-rate 1.0 ml/min; UV detection 254 nm; reaction time 330 h at 25°C. Peaks: 1 = $Ga(TIB)_3$; 2 = $Ga(TFA)(TIB)_2$; 3 = $Ga(TFA)_2(TIB)$; 4 = $Ga(TFA)_3$.

dence of on-column redistribution although degradation of the indium did presumably occur.

Ligand-exchange reactions between gallium and copper chelates

$Cu(TFA)_2$ was allowed to react with $Ga(TTB)_3$ in a 1:1 molar ratio according to the conditions described in Table I and the reaction products were chromatographed. Four resultant peaks are shown in Fig. 5, identified by comparing the retention times with those of the peaks obtained from the reaction between $Ga(TFA)_3$ and $Ga(TTB)_3$. Copper chelates could not be eluted under the experimental conditions employed and therefore only the gallium chelates appeared on the chromatograms.

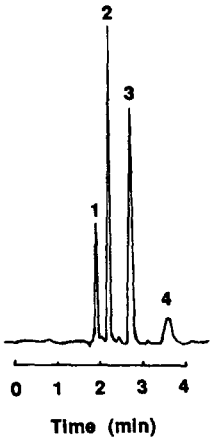


Fig. 5. HPLC separation of mixture of ligand-exchange reaction products formed from $Ga(TTB)_3$ and $Cu(TFA)_2$. Column 5 μm silica, 150 × 4.6 m I.D.; mobile phase THF–heptane (14:86, v/v); flow-rate 1.0 ml/min; UV detection 254 nm; reaction time 24 h at 25°C. Peaks: 1 = $Ga(TTB)_3$; 2 = $Ga(TFA)(TTB)_2$; 3 = $Ga(TFA)_2(TTB)$; 4 = $Ga(TFA)_3$.

$Ga(TFA)_3$ was then allowed to react with $Cu(TTB)_2$ (1:1) to yield a chromatogram which was virtually identical with that in Fig. 5. The reaction between $Cu(TFA)_2$ and $Ga(TTB)_3$ apparently proceeded to give products identical to those from the reaction between $Ga(TFA)_3$ and $Cu(TTB)_2$.

It was concluded that the ligand-exchange reactions between gallium and copper fluorinated β-diketone chelates occurred in liquid phase with no ligand distribution bias due to the difference in structure between the gallium (octahedral) and copper (tetrahedral) complexes.

Ligand-exchange reaction between gallium and nickel chelates

$Ga(TTB)_3$ was allowed to react with $Ni(TFA)_2$ (1:1) under conditions described in Table I, giving rise to a chromatogram similar to that in Fig. 5. Although the nickel chelates were not eluted from the column, the ligand-exchange reaction was shown to have occurred in the liquid phase. In this case, the reactant nickel complex was probably trimeric, but this did not appear to perturb the redistribution pattern.

CONCLUSION

This study shows that the normal-phase HPLC for these metal complexes is highly dependent upon the metal atom present. However, all of the ligand redistributions investigated were shown to have taken place in the liquid phase under the ambient temperature reaction conditions employed. The kinetics of representative ligand-redistribution reactions may be obtained from further HPLC studies.

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