Catalytically-Promoted Analyte Derivatization Inside a Gas Chromatographic Inlet

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Abstract

Reported here is a preliminary assessment of the feasibility of catalyzing on-line derivatization reactions inside the inlet (i.e., the injection port) of a gas chromatograph (GC) with solid heterogeneous catalysts. The experiments described here entail the installation of candidate catalysts inside the GC inlet liner and the subsequent injection of analyte/reagent mixtures onto the catalyst beds. Two catalysts are identified, each of which clearly catalyzes one of the chosen model derivatization reactions in the inlet of a GC. This result supports our hypothesis that on-line derivatizations can, in principle, be reproducibly catalyzed inside the GC inlet by solid heterogeneous catalysts and that the presence of such catalysts in the inlet do not necessarily cause a serious loss of instrument performance or chromatographic efficiency.

Introduction

Because of the inherent simplicity and effectiveness of gas chromatography (GC), analytical chemists have long attempted to apply the GC technique even to determinations of "difficult" analytes, i.e., those that are too labile, too polar, too adsorptive, too nonvolatile, or too weakly responsive in the available GC detectors to be readily determinable by conventional GC. One major strategy for accomplishing this goal has been to chemically derivatize the analytes to form derivatives that offer improved properties and that can substitute for the original analytes in the analysis step. Most such derivatizations are done "off-line" in a reaction vessel that is separate from the GC analysis hardware. But conducting the derivatization "on-line", i.e., simultaneously with the analysis step by injecting the sample/reagent mixture directly into the hot GC inlet, can eliminate time-consuming sample-processing steps, reduce measurement errors and interferences, and decrease the amounts of valuable and/or toxic reagents, solvents, and sample materials that would otherwise be needed (1–8).

One drawback to conducting on-line derivatizations is that the various factors affecting the success of the derivatization process are not well-understood. As an example, Tornes and Johnsen (9) reported the on-line derivatization and determination of methylphosphonic acid and several alkyl methylphosphonic acids, which result from the environmental breakdown of certain chemical warfare agents, down to 2 ng/mL in water. This method was ultimately repeated successfully in another laboratory but only after these investigators packed their GC inlet liner with deactivated fused-silica wool and fused-silica beads "to provide additional surface area which might promote reaction" (10). But when yet another research group attempted to repeat the original work, they were completely unable to observe a response to derivatized methylphosphonic acid at concentrations below 100 µg/mL in their water samples (11).

Indeed, there appears to be significant uncertainty as to exactly where, inside the GC system, on-line derivatization reactions actually take place. Note that these reactions could, in principle, occur in the liquid phase within the rapidly evaporating droplets of injected liquid solution, in the gas phase after the injected solution has evaporated, or on the interior surfaces of the inlet or column.

However, there is evidence to suggest that the inner surfaces of the inlet are intimately involved in at least some on-line derivatizations. In addition to the previously cited example (10), it has been noted that the array of methylation products obtained in a GC inlet from multi-functional analytes during on-line derivatization with quaternary ammonium reagents varies with the "condition" of the deactivated glass GC inlet liner (12) and that a thoroughly used, contaminated liner yields better methylation efficiency than a clean, new one (13). In another study, which was conducted with a packed GC column, efficient alkylation of thiocyanate ion was achieved only after extending the packed portion of the column about 2 cm into the GC inlet, leading the authors to conclude that "the alkyl transfer reaction is facilitated by hot surfaces, such as provided by the segment of heated column packing" that protruded into the inlet (14). Note that, despite this evidence for inlet-surface involvement in derivatization reactions, these and several other investigators have referred to their GC-based on-line derivatizations as "on-column" derivatizations (2,3,12–15).

One additional problem with current GC inlet-derivatization approaches is that the inlet (or other front-end sample-vaporizing hardware) commonly must be maintained at a rather high temperature, e.g., from 250°C to as much as 500°C or more, to

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drive the intended derivatization reactions to completion. Unfortunately, these rather elevated temperatures also tend to promote unwanted and uncontrolled thermal decompositions and other side reactions, including decarboxylations, dehydrations (and other dehydroxylations), double-bond migrations, and molecular re-arrangements (16–19). In addition, large amounts of chemically aggressive reagents have been required in some instances to drive the desired derivatizations to completion. These large reagent loadings have led to problems with system overloading, inlet fouling, column deterioration, and memory effects (12,17).

Perhaps fortuitously, most of the major types of analytical derivatization reactions, including alkylation, trimethylsilylation, and acylation reactions, entail replacement of an active hydrogen atom on the analyte molecule with a more inert (or otherwise more favorable) displacing functional group. Because of this kinship among the major reaction types and also because of the likelihood of surface mediation of these reactions in on-line mode, one can hope that a few simple catalysts can be found that will effectively promote a wide range of derivatizations and that will significantly reduce the temperatures and/or reagent concentrations needed to drive the derivatization reactions to completion. It is also noteworthy that on-line derivatizations are now being done with the use of conventional deactivated glass inlet liners, gold-plated seals, and other highly inert materials that are intended to minimize, rather than maximize, the occurrence of inside-the-inlet chemical reactions. Thus, the use of a suitable solid heterogeneous catalyst inside the GC inlet may lead to improved performance and hence broader acceptance of the on-line derivatization technique in GC analysis. Described below is a preliminary screening and evaluation of catalysts for this purpose. It must be emphasized that this is merely a feasibility study, i.e., an early test of the prospect of catalyzing on-line derivatizations in the GC inlet. Hence, this paper does not, and is not intended to, describe a completed and validated method of analysis.

Table I. Tested Derivatization Reagents

Reagent name	CAS Registry No.	Displacing group
Trimethylphenylammonium chloride (TMPAC)	138-24-9	Methyl
Trimethylsulfonium iodide (TMSI)	2181-42-2	Methyl
Hexamethyldisilazane (HMDS)	999-97-3	Trimethylsilyl
N,O-bis(Trimethylsilyl)trifluoroacetamide (BSTFA)	25561-30-2	Trimethylsilyl
N-trifluoroacetylimidazole (TFAI)	1546-79-8	Trifluoroacetyl
N-Methyl-bis(trifluoroacetamide) (MBTFA)	685-27-8	Trifluoroacetyl

Table II. Tested Analytes

Analyte name	CAS Registry No.	Active functional group
Ethyl methylphosphonic acid (EMPA)	1832-53-7	Acidic OH
Carbazole (CZ)	86-74-8	Weakly basic NH
Methyl salicylate (MES)	119-36-8	Weakly acidic OH
N-methylacetamide (NMA)	79-16-3	Weakly basic NH
4-Methylbenzyl alcohol (MBA)	589-18-4	Neutral OH
2-Methyl-1-butanethiol (MBT)	1878-18-8	Neutral SH
2,3-Dihydro-3-oxobenzisosulfonazole (saccharin) (SAC)	81-07-2	Acidic NH
Acetylsalicylic acid (aspirin) (ASA)	50-78-2	Acidic (carboxylic) OH
α-Methyl-4-(2-methylpropyl) benzeneacetic acid (ibuprofen) (IBU)	15687-27-1	Acidic (carboxylic) OH
Nicotinic acid (niacin) (NA)	59-67-6	Acidic (carboxylic) OH
8-Hydroxyquinoline (HQ)	148-24-3	Acidic (phenolic) OH
Tetrahydro-1,4-oxazine (morpholine) (MOR)	110-91-8	Basic NH
o-Cresol (CRE)	95-48-7	Acidic (phenolic) OH
4-Methylbenzenethiol (MT)	106-45-6	Acidic SH
p-Toluenesulfonic acid (• H_2O) (TSA)	6192-52-5	Acidic SO_3H

Experimental

Reagents, analytes, and other chemicals

The derivatization reagents and model analytes that were tested in this study are listed in Tables I and II, respectively, along with the acronyms used throughout this paper in referring to them. The reagent *N*-methyl-bis(trifluoroacetamide) (MBTFA) was obtained from Fisher Scientific (Waltham, MA). All other noncatalyst reagents, analytes, solvents, and other chemicals were obtained from Sigma Aldrich (St. Louis, MO) in reagent-grade or equivalent purity. The reagents in Table I were chosen for evaluation because they or their closely related analogs have been touted previously for use in on-line GC-inlet derivatizations; they were expected to be relatively low in reactivity, leading to a relatively high probability of attaining the desired incomplete derivatizations; and they covered several of the available chemical functionalities, as described to some degree in the last column of the table. Moreover, it should be mentioned that some of the analytes in Table II proved to be readily detectable as well-formed GC peaks, even without derivatization. However, this fact was not deemed as sufficient cause for rejection of the pertinent analytes from this test program, as this characteristic should not have influenced the ability of the analytes in question to derivatize or to demonstrate catalytic activity in a derivatization reaction.

Catalysts

The candidate catalysts that were procured for evaluation are listed in Table III, along with their commercial sources. Some of these are actually marketed as catalyst "supports" and/or "carriers" but were nonetheless screened as-is due to their known stand-alone Lewis acidity or basicity. Owing to a variety of issues, as described later, some of the catalysts listed in Table III were not screened or were subjected to only partial screening. All of the catalysts in Table III were believed to be thermally stable and therefore unlikely to melt, fuse, or vaporize at temperatures up to 300°C in a helium atmosphere, and no evidence to the contrary was turned up during the course of this work.

Instrumental conditions

All tests were performed on an Agilent Model 6890 GC system equipped with an Agilent Model 5973 mass selective detector

(MSD) (Santa Clara, CA). This instrument featured electron impact ionization at 70 eV, as well as a NIST 98 (version 2.0) mass spectral library. The instrument was operated in total-ion (i.e., full-scan) mode with scanning from 45 to 550 atomic mass units (AMU). The temperatures of the MSD quadrupole, the GC–MSD interface, and the ion source were, respectively, 150, 280, and 230°C. The carrier gas flow (He, 1.0 mL/min) was driven in constant-flow mode. In all tests, the GC inlet utilized a simple cylindrical deactivated glass inlet liner (Catalog No. 4924, Grace Davison Discovery Sciences, Deerfield, IL). This item featured a quartz-wool plug whose upper end, in the absence of a catalyst, was situated just beneath the point where the syringe needle tip resided during an injection. All injections were splitless with a split-vent delay of 1.0 min and a purge flow of 50 mL/min. The column was a Phenomenex (Torrance, CA) ZB-5 fused-silica capillary (30 m × 0.25-mm i.d., 0.5-µm film thickness, Catalog No. 7HG-G002-17). All tests entailed the use of column temperature programming; the most frequently used program was as follows: isothermal at 50°C for 1 min, ramp at 20°C/min to 210°C, then hold to end of run.

Baseline testing procedure

Before catalyst testing could begin, we had to identify several "model" derivatization reactions that proceeded inefficiently in our GC system at low inlet temperatures in the absence of a catalyst. Note that only when the derivative recovery is demonstrably low in the absence of a catalyst can any subsequent enhancement in recovery due to a catalytic effect be observed. The preliminary tests that were performed to establish the existence of a low derivative recovery in the absence of a catalyst were termed "baseline tests" for each model derivatization reaction.

In carrying out the baseline tests, we injected each analyte/reagent combination into the GC–MSD with no catalyst installed in the inlet. In a typical test, 1 µL of an acetonitrile solution containing an analyte (25 µg/mL), a nonderivatizable internal standard (IS, naphthalene, 25 µg/mL), and a derivatization reagent was injected into the GC–MSD inlet. The concentration of the derivatization reagent in this mixture was 2.5 mg/mL for the solid reagents (TMPAC, melting point = 246–248 °C; and TMSI, melting point = 215–220 °C) and 5% (v/v) for all other reagents. These concentrations represented large stoichiometric excesses over the minimum amounts needed for quantitative derivatization of the injected analytes. The test mixture was generally prepared just prior to the injection step to minimize the extent of derivatization occurring outside the GC–MSD inlet (i.e., in the solution phase) prior to injection. All of the tested analytes appeared to be completely soluble in acetonitrile at the stipulated test concentrations. Analyte derivative peaks in the chromatograms were identified primarily from their electron-impact mass spectra. In addition, "control" samples, which contained only the reagent and the IS (i.e., no analyte) were also injected to assist in identifying key chromatographic peaks and to check for problems with analyte or derivative "carryover" from previous injections. All responses to the derivatives were measured and recorded relative to that for the IS.

For the baseline tests, injections into the GC–MSD were performed both at relatively high inlet temperatures (i.e., typically 250–300°C), which were expected to represent favorable conditions for maximizing derivative yield, and at significantly lower

Table III. Candidate Catalysts Purchased for Evaluation in This Study

Catalyst name	Source	Catalog No.	Physical form	Surface area, m^2/g	Comments
Montmorillonite K 10	Sigma Aldrich	281522	Fine powder	250	pH 3–4
Montmorillonite K 10 with $ZnCl_2$	Sigma Aldrich	96476	Fine powder	250	Contains 0.35 mmol/g ZnCl2
Montmorillonite KSF	Sigma Aldrich	281530	Fine powder	30	pH 1–2
Montmorillonite K 30	Sigma Aldrich	69904	Fine powder	330	pH 2.8–3.8
Montmorillonite, untreated	Sigma Aldrich	69911	Fine powder	Unknown	pH 5–8
Bentonite	Sigma Aldrich	18609	Fine powder	Unknown	pH 8
Al_2O_3/SiO_2 (82.1%/17.9%)	Alfa Aesar	43856	1/8" pellets	30	Catalyst support
Al_2O_3, alpha phase	Alfa Aesar	42901	4-mm pellets	3–7	Catalyst support, now discontinued
Al_2O_3, gamma phase	Alfa Aesar	43832	1/8″ pellets	255	Catalyst support
SiO_2	Alfa Aesar	44741	1/8″ pellets	160	Catalyst support
ZrO_2	Alfa Aesar	43814	1/8″ pellets	90	Catalyst support
TiO_2	Alfa Aesar	43828	1/8″ pellets	37	Catalyst support
CaO	Sigma Aldrich	208159	fine powder	Unknown	Reagent chemical
$Ca(OH)_2$	Sigma Aldrich	239232	fine powder	Unknown	Reagent chemical
$FeMoO_4$	Sigma Aldrich	541230	fine powder	Unknown	Reagent chemical
ZnSe	Sigma Aldrich	244619	fine powder	Unknown	Reagent chemical
Nb_2O_5	Sigma Aldrich	383031	coarse lumps	Unknown	Reagent chemical
JR 323 basic alumina carrier	St.-Gobain NorPro	CRR** RD4	1/4" rings	250	Catalyst carrier
LS-401	Unicat Catalyst Technologies	NA	5-mm pellets	120	Low temperature shift catalyst
Activated carbon	Lab Safety Supply	1A-11724	12/28-mesh granules	~1000	Coconut carbon
Zeolite Beta, S/A = 25	Zeolyst International	CP 814E	Powder	680	Cation = ammonium
Zeolite Beta, S/A = 360	Zeolyst International	CP 811C-300	Powder	620	Cation = hydrogen
Ferrierite, S/A = 20	Zeolyst International	CP 914C	Powder	400	Cation = ammonium
Ferrierite, S/A = 55	Zeolyst International	CP 914	Powder	400	Cation = ammonium

inlet temperatures, where the yield was required to be less than 50% of that obtained at the higher temperature. This was done to ensure that during the subsequent catalyst tests, which were performed at the lower inlet temperatures, the inherent derivative yield would be low enough that any enhancement in yield due to a catalytic effect could, in fact, be clearly observed. Moreover, all tests with a given analyte-reagent combination were performed at least in triplicate, and all replicate results were required to exhibit less than 20% relative standard deviation (RSD). Only those reactions that met these criteria were deemed acceptable for use as model reactions in the subsequent catalyst tests.

Catalyst installation

For naturally granular catalysts, grains of catalyst on the order of 1 to 2 mm in their longest dimension were selected individually with forceps and dropped one-by-one onto the top of the quartz-wool plug that resided inside the GC inlet liner. This process was continued until a catalyst bed depth of approximately 2 mm in the inlet liner was achieved. For catalysts that were furnished in pellet form, a single pellet was either dropped intact into the liner (on top of the quartz-wool plug) or was crushed to a granular consistency before being deposited into the liner in the manner just described for granular catalysts. For finely powdered catalysts, we compressed a 0.1-g portion of the catalyst in a pellet press to obtain a ca. 0.5-mm thick solid wafer, fractured the wafer to a granular consistency, and proceeded as described for granular catalysts. This procedure for testing powdered catalysts has been used previously for catalyst evaluations in flowing gas streams (20).

Prior to the testing of each catalyst-packed liner, the quartz-wool plug supporting the catalyst bed was repositioned inside the inlet liner such that the catalyst bed resided just beneath the tip of the syringe needle during the injection step. Thus, once the catalyst-packed liner was installed in the instrument, all solutions were injected directly onto the top of the catalyst bed without contacting the bed with the syringe needle tip. A fresh (new) liner was used for each individual catalyst and was not subsequently used for any other purpose in this study, either with or without a catalyst.

Catalyst testing procedure

To screen the candidate catalysts for efficacy in this application, we repeated the injections and measurements that were described earlier in connection with baseline testing for each of the acceptable model derivatization reactions. This time, however, the catalyst-packed inlet liners, rather than the unpacked liners, were installed in the GC–MSD instrument. For each reaction, these tests were performed at the "lower inlet temperature" as established in the baseline tests, i.e., the temperature at which the derivative yield for that reaction was less than 50% of that obtained at the "higher inlet temperature". This was done to ensure that any catalytic enhancement of the derivative recovery could be readily observed. The IS-corrected responses to the derivatives in the presence of the catalysts were required to exhibit less than 20% RSD, as described previously for the baseline tests. Data meeting this requirement were compared to the corresponding baseline responses to gauge the presence or absence of a catalytic effect. An apparent catalytic effect was considered both real and significant if the catalyst increased the average derivative yield by 50% or more relative to the average baseline derivative yield. When an apparent catalytic effect was

Table IV. Catalytic Derivative Recoveries Expressed as Percentages of the Baseline Recoveries

Model Reactions → Catalysts ↓	TMPAC/EMPA	TMPAC/ASA	TMPAC/TSA	TMSI/EMPA	TMSI/ASA	MBTFA/MT	MBTFA/MBA
Al_2O_3, alpha phase	0	0	0	0	0	0	253
Al_2O_3/SiO_2 (82.1%/17.9%)	0	0	0	0	0	76	16
Al_2O_3, gamma phase	0	54	0	0	0	0	55
SiO_2	0	77	0	0	0	26	60
ZrO_2	0	43	0	0	0	115	0
TiO_2	0	0	0	0	38	0	34
CaO*	0	0	0	0	0	47	NT†
$Ca(OH)_2$*	0	0	0	0	0	65	38
LS-401 (Unicat)	0	0	0	0	0	0	20
JR323 (St.-Gobain NorPro)	0	0	0	0	0	0	1
Montmorillonite KSF	0	0	0	0	0	293	21
Montmorillonite K 10	NT	NT	NT	NT	NT	0	0
Montmorillonite K 30	0	0	0	0	0	0	0
Montmorillonite K 10/$ZnCl_2$	NT	NT	NT	NT	NT	NT	0
montmorillonite, untreated	NT	NT	NT	0	0	NT	0
Bentonite	0	0	0	0	0	0	20
Activated Carbon	NT	NT	NT	0	0	NT	NT
$FeMoO_4$	0	0	0	0	0	73	95
Nb_2O_5	0	35	14	0	0	0	138
ZnSe	0	29	0	NT	0	0	95

* Following the tests of calcium oxide and calcium hydroxide, an instrument problem was discovered; and thus the data for these two catalyst candidates should be regarded as suspect.
† NT = Not tested.

observed, both the baseline tests and the catalyst tests were repeated together on the same day and once again were held to the same acceptance criteria as applied previously. This was done to preclude the possibility that the data were affected by changes in instrument response over longer time periods.

Results and Discussion

Baseline test results

Early in the test program, we attempted to use ethyl acetate rather than acetonitrile as the reaction solvent for the derivatization reactions. During this period, all of the derivatization reagents in Table I were tested with each candidate analyte in Table II. However, the reagent *N*-trifluoroacetyl-imidazole (TFAI) yielded grossly elevated chromatographic baselines in conjunction with all of the Table II analytes and was therefore not subjected to further testing. Except for this result with TFAI, the amounts of likely reagent decomposition products observed in the test chromatograms invariably appeared to be small relative to the amounts of reagent injected. Ultimately, we found nine reagent-analyte combinations that met all of the previously stated criteria for a useful model derivatization reaction: trimethylphenylammonium chloride (TMPAC)- ethyl methylphosphonic acid (EMPA), TMPAC-acetylsalicylic acid (ASA), TMPAC-*p*-toluenesulfonic acid (TSA), TMPAC-nicotinic acid (NA), trimethylsulfonium iodide (TMSI)-EMPA, TMSI-ASA, MBTFA-MT, MBTFA-4-methylbenzyl alcohol (MBA), and hexamethyldisilazane (HMDS)-MBA. For each of these reactions, the observed analyte derivative was the one that was expected assuming displacement of the active hydrogen from the analyte molecule (Table II) by the displacing group from the reagent (Table I).

But we eventually encountered serious chromatographic interferences during the subsequent catalyst tests, which appeared to be related to an adverse interaction between the ethyl acetate reaction solvent and several of the catalysts. The nature of these interferences varied with the catalyst, but they generally manifested themselves as major baseline upsets and/or losses of response to the IS and/or to the analyte derivatives. On more than one occasion, the GC column's performance was severely and permanently degraded, necessitating removal of the column and thorough cleaning of the inlet before installing a new column. As a result of this experience, the Zeolite Beta and Ferrierite catalysts were dropped from the test program, and ethyl acetate was replaced with acetonitrile as the reaction solvent.

After the switch to acetonitrile, our instrumental response problems generally appeared to be much less severe. But on re-evaluating our nine tentative model derivatization reactions in the new solvent, we found two (HMDS-MT and TMPAC-NA) that no longer met the previously stated acceptance criteria. Hence, we proceeded into the catalyst-testing phase of the project with the remaining seven model reactions, as follows: TMPAC-EMPA, TMPAC-ASA, TMPAC-TSA, TMSI-EMPA, TMSI-ASA, MBTFA-MT, and MBTFA-MBA.

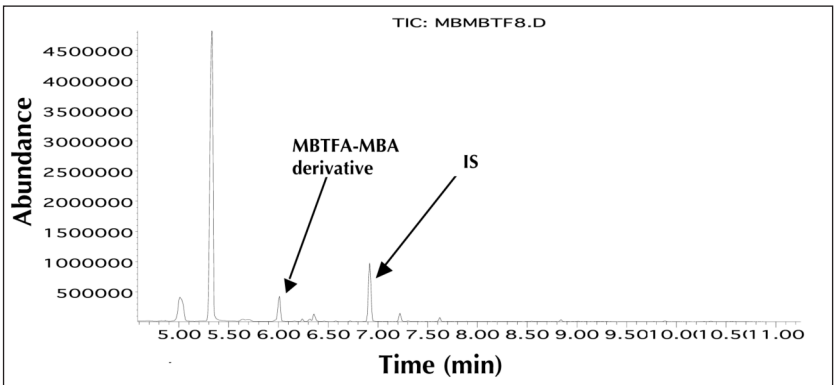

Figure 1. Typical total-ion chromatogram obtained for MBTFA-MBA with the alpha-phase alumina catalyst (Alfa Aesar Cat. No. 42901) installed in the GC–MSD inlet.

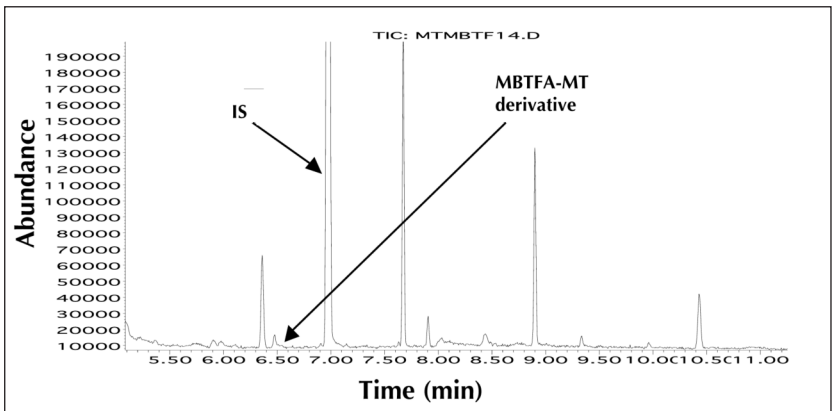

Figure 2. Typical total-ion chromatogram obtained for MBTFA-MT with the Montmorillonite KSF catalyst installed in the GC–MSD inlet.

Catalyst test results

The results of the catalyst tests are summarized in Table IV, where the IS-corrected derivative recoveries in the presence of the catalysts are expressed as percentages of the corresponding recoveries in the absence of the catalysts. In this table, a derivative recovery of zero indicates that no derivative response was observed. Note also that some catalysts in Table IV, owing to time constraints and/or interference problems, were not tested with certain model reactions.

To be reasonably certain that an apparent catalytic effect was indeed real, we required the catalytic derivative recovery to be at least 150% of the corresponding baseline derivative recovery. Hence, it is apparent from Table IV that two combinations of derivatization reaction and catalyst easily met this requirement: MBTFA-MBA on alpha-phase aluminum oxide (alumina) and MBTFA-MT on Montmorillonite KSF. Furthermore, the chromatographic peak shapes for the derivatives and the IS were not significantly different from those obtained in the absence of the catalysts, and there was no significant carryover of derivatives or underivatized analytes from one

sample into subsequent analyte-free control-sample analyses. In addition, the IS peak areas obtained with the catalysts installed were essentially the same as those from the corresponding baseline tests, where no catalysts were used. Typical total-ion chromatograms for these two catalyst-reaction combinations are shown in Figures 1 and 2.

The derivatives that were expected from these reactions were 4-methylbenzyl trifluoroacetate (from MBTFA-MBA) and 4-methylphenyl trifluoroacetyl sulfide (from MBTFA-MT). The measured mass spectra of the derivatives are depicted in Figure 3. These spectra appear to be fully consistent with the structures of the anticipated derivatives. For example, both spectra feature prominent molecular ions at the expected masses and one or more significant fragment ions at masses that relate in a straightforward manner to moieties within the proposed molecular structures. The unidentified peaks observed in Figures 1 and 2 and in all other recorded chromatograms were generally found to be due to reagent, analyte, and solvent impurities, column bleed products, underivatized analytes, products of the derivatization reaction, and products of the partial thermal decomposition of the derivatizing reagent. Moreover, no obvious instabilities in derivative or internal standard retention times were observed, and there were no data trends suggesting a potential problem with the concept of re-using a catalyst-packed inlet liner for multiple sample analyses.

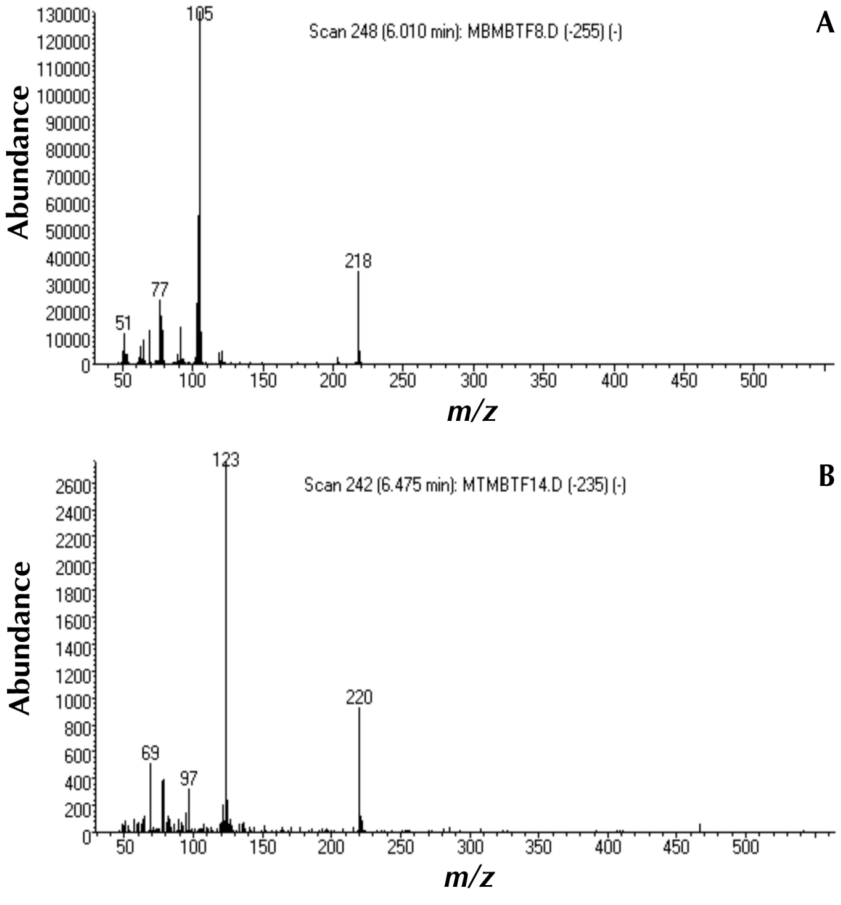

Figure 3. Electron-impact mass spectra of the MBTFA-MBA derivative (A) and the MBTFA-MT derivative (B).

Unfortunately, the data do not provide many clues as to why catalytic activity was observed only for alpha-phase alumina and Montmorillonite KSF and only for two of the seven model reactions. Indeed, the two model analytes in question appear to have little in common with one another, aside from the presence of a benzene ring in their structures. The alpha alumina, which has since been dropped from the vendor's product line and is no longer available commercially, was supplied as a 4-mm diameter pellet with a rather low surface area (3–7 m^2/g). Alumina, when heated to more than 1000°C, undergoes repeated phase changes and losses of surface area until it finally attains the alpha phase, which is the most stable and lowest surface-area state for this substance (21). Its catalytic properties and Lewis acidity tend to be sensitive functions of the types and amounts of any impurities and dopants that may be present, the thermal and chemical history of the material, the extent of its crystallinity, the nature and prevalence of any structural defects, the extent of occurrence of any transitional phases in the material, and the extent of dehydration (i.e., activation) of the normally hydrated material.

Montmorillonite KSF is a naturally occurring clay mineral that has been fortified by the manufacturer with sulfuric acid and possibly with other mineral acids as well. The native (untreated) montmorillonite clay has both Bronsted and Lewis acid properties (22). Its layered structure provides favorable reaction conditions for many substances. In particular, the confining two-dimensional character of the available reaction space causes molecular encounter rates, and therefore reaction rates, to be higher than they are for the more typical three-dimensional cases (22). Its surface area is about 30 m^2/g. Of the montmorillonite-based products that were tested, only Montmorillonite KSF and Montmorillonite K 30 produced reasonably low chromatographic baselines. Hence, only limited testing was carried out with the other montmorillonites. Montmorillonite KSF was the most acidic and the lowest in surface area of the montmorillonite-based catalysts that were tested.

We noticed that both of the successful catalysts offered moderately low surface areas relative to most of the other catalysts. This fact prompted us to speculate that, although some porosity may be desirable in this application, the existence of too much surface area in the catalyst may actually tend to cause excessive losses of the derivatives, possibly through irreversible or quasi-irreversible adsorption of those species. Indeed, the data of Table IV indicate that, at least for TMPAC- and TMSI-based reactions, the derivatized analytes seldom even passed through the catalysts in detectable amounts. Accordingly, it seems likely that the methylated, and still somewhat polar, products of these reactions (and possibly the reactants as well) were adsorptively trapped and retained by the catalysts with high efficiency. And yet,

the nonpolar IS compound (naphthalene) generally passed through the catalysts without significant attenuation. These observations seem to argue in favor of limiting the surface area, if not necessarily the polarity or acidity, of future candidate catalysts for this application.

The fact that both of the successful derivatizations were conducted with the reagent MBTFA was an interesting and potentially quite significant outcome. Because the derivatives from the reagents TMPAC and TMSI tended to be quantitatively trapped or consumed by the catalysts more frequently than those from the reagent MBTFA (Table IV), it is reasonable to presume that the properties of MBTFA and/or its derivatives were somehow critical to the successful observation of catalysis for the two derivatizations described earlier. Therefore, we hypothesized that the presence of the trifluoromethyl group in the MBTFA derivatives markedly reduced the polarity, or at least the adsorptive potential, of these derivatives and thereby diminished the adsorptive losses that possibly plagued the other reactions. This suggests that any use of a solid heterogeneous catalyst in the inlet of a GC instrument may ultimately be most successful for those derivatization reactions that can cause the greatest reductions in the inherently adsorptive nature of polar analytes.

Conclusion

In this initial study, we demonstrated that the concept of catalyzing the on-line derivatization of polar analytes with solid heterogeneous catalysts inside the inlet of a GC is fundamentally feasible. In particular, this work shows that catalytically-promoted derivatization can be effected in a reproducible manner without immediately degrading GC instrument performance, without significant carryover of the analyte derivative (or the underivatized analyte) into subsequent sample analyses, and without a concomitant loss in derivative peak shape or chromatographic efficiency. Future work should focus on learning more about the critical requirements for catalysts and derivatization reactions, as well as the requirements for successful recovery of derivatized analytes from catalysts, in this application.

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