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ABSTRACT: When dealing with trace analysis of complex mixtures, NMR suffers from both low sensitivity and signal overlap. NMR chemosensing, in which the association between an analyte and a receptor is "signaled" by an NMR response, has been proposed as a valuable analytical tool for biofluids and natural extracts. Such chemosensors offer the possibility to simultaneously detect and distinguish different analytes in solution, which makes them particularly suitable for analytical applications on complex mixtures. In this study, we have combined NMR chemosensing with nuclear spin hyperpolarization. This was realized using an iridium complex as a receptor in the presence of parahydrogen: association of the target analytes to the metal center results in approximately 1000-fold enhancement of the NMR response. This amplification allows the detection, identification, and quantification of analytes at low-micromolar concentrations, provided they can weakly associate to the iridium chemosensor. Here, our NMR chemosensing approach was applied to the quantitative determination of several flavor components in methanol extracts of ground coffee.
Because of their low concentrations, further aggravated by signal crowding, most of these volatile species are not detectable by routine NMR methods. However, several of them (e.g., pyridine and pyrazine derivatives) weakly associate to metalorganic iridium complexes in a methanol solution. Here we demonstrate that their signals can be selectively detected by hyperpolarized NMR chemosensing techniques. Thanks to the selective amplification of the NMR chemosensor response, we could quantitatively detect target components at micromolar concentrations.

### EXPERIMENTAL SECTION

**Coffee Sample**. A commercially available vacuum-packed ground coffee sample was purchased from a local grocery market in The Netherlands. This sample was declared as “regular” coffee of Arabica variety, with medium degree of roast and medium-scale grinding, designed to be normal filter coffee.

**Chemicals**. Complex precursor [Ir(COD)(IMes)Cl] (IMes = 1,3-bis(2,4,6-trimethylphenyl)imidazole-2-ylidine; COD = cyclooctadiene) and cosubstrate 1-methyl-1,2,3-triazole (mtz) were synthesized according to published methods. Methanol-d₄ was purchased from Cambridge Isotope Laboratories. All other chemicals were purchased from Sigma-Aldrich (pyridine, pyrazine, 2-methylpyrazine, 2-ethylpyrazine, 2,6-dimethylpyrazine, 3-hydroxyypyridine). Parahydrogen (p-H₂) was produced with an in-house designed 2 L vessel embedded in a liquid nitrogen bath. Normal hydrogen (purity 5.0) was cooled down to 77 K in the presence of 100 mL of 4–8 MESH charcoal (Sigma-Aldrich). The resulting 51% p-H₂ was transported to an aluminum cylinder (Nitrous Oxides Systems, Holley Performance Products, Bowling Green, KY, USA), with an adjustable output-pressure valve.

**Methanol Extraction**. Ground roasted coffee (1.8 g) was suspended in methanol-d₄ (5 mL) and stirred for 30 min at room temperature. After centrifugation, the supernatant was collected with a syringe, leaving behind a soggy coffee residue. The liquid was filtered using a 0.45 μm MF-Millipore MCE Membrane Filter Unit by Millex.

**NMR Sample Preparation**. A stock solution of 4.8 mM [Ir(COD)(IMes)Cl] complex precursor, 72 mM 1-methyl-1,2,3-triazole (mtz) as cosubstrate, and 100 mM ethanol as a reference was prepared in methanol-d₄ under nitrogen pressure. Prior to the NMR measurements, 120 mg of stock solution, corresponding to 1/4 of the final NMR sample volume, was transferred into a 5 mm Wilmad quick pressure valve (QPV) NMR tube. The tube was pressurized under 5 bar of H₂ to convert the complex precursor into the activated symmetric complex [Ir(IMes)(H)₂(mtz)₃]Cl. Complete activation required approximately 120 min. Immediately before the NMR measurements, 360 mg of coffee extract (3/4 of the total NMR sample volume) was added to the activated catalyst solution in the QPV NMR tube. Final concentrations of the stock solution components were 1.2 mM iridium complex, 18 mM mtz, and...
25 mM ethanol, while the coffee extract components were diluted to 75%.

**Standard Addition.** For the standard addition experiments stock solutions (100 mM and 1 mM) of the compound under investigation were prepared using coffee extract in methanol-d₄ as a solvent. A typical standard addition series consisted of the original coffee extract and four additional samples at increasing concentration of the analyte. Typically, the highest analyte concentration in the series corresponded to ca. 2.5−4 times the original concentration in the coffee extract. All solutions were prepared by gravimetric mixing of solvents and analytes, assuming for all methanolic extracts and solutions a density equal to methanol-d₄ (0.888 g/mL).

**Theory.** In the following we will refer to the species that can bind to the chemosensing receptor as “analytes” or “substrates”, interchangeably. We have previously shown¹⁵ that in the presence of a dilute target analyte and a large excess of mtz, the activated symmetric complex [Ir(IMes)(H)₂(mtz)₃]Cl is partly converted into the asymmetric complex (1) (see Figure 1A in the case of a pyridine derivative). Because of the chemical inequivalence of the two hydrides, the p-H₂ derived singlet state is rapidly dephased, leaving longitudinal spin order as surviving term.²⁹,³⁰ The SEPP³¹,³² NMR pulse scheme displayed in Figure 1B allows the conversion of such longitudinal spin order into hydrides enhanced magnetization, which can be detected as an NMR signal increased up to 3 orders of magnitude. We have recently shown that this spin-order can also be exploited to enhance the NMR signals of analyte protons in the metal complex via long-range scalar couplings.²⁴

The 2D pulse scheme here employed (Figure 1C) differs from the previously presented one²⁴ in that a “forth-and-back” coherence transfer pathway is followed, with acquisition on the hydrides rather than on aromatic protons of the substrate. After the initial SEPP block, hydrides enhanced magnetization is transferred via homonuclear-INEPT³³ to the analyte protons for t₁ evolution and then back, following a Homonuclear Single
Quantum Coherence (HoSQC) pathway. We have recently proposed a similar scheme for the determination of the long-range coupling constants between hydride and substrate protons. The acquired 2D spectrum correlates the hydrides with the substrate protons in the bound form only; no NMR signal from free molecules in solution is observed with the proposed experiment. Analogously, the symmetric complex [Ir(IMes)(H)₂(mtz)₃]Cl is not detected by this 2D SEPP-HoSQC experiment, due to the chemical equivalence of the two hydrides. The coherence transfer along the pulse sequence is illustrated in Figure 1C at specific time points in terms of product operator formalism for a spin system consisting of two hydrides (A and X) and two ortho protons (M₁ and M₂); this description can be extended to more complex spin systems.

NMR. All NMR spectra were acquired at 283 or 298 K and at 499.91 MHz 1H resonance frequency using a Varian UnityInova 500 spectrometer equipped with a triple-resonance HCN room temperature probe, with a shielded z-gradient coil. Typically, 2D data matrices consisting of 48(t₁) × 2400(t₂) complex points were acquired with eight scans per increment in ca. 20 min. The 2D data sets were processed with NMRPipe or iNMR, using 72° shifted squared sine-bell apodization in both dimensions, prior to zero filling to 1024(t₁) × 16384(t₂) complex points, and Fourier transformation.

■ RESULTS

NMR investigations of coffee conducted so far have mostly focused on species at relatively high concentrations (typically mM). Conversely, concentrations in the methanol extract are expected between high nM and sub-mM for several flavor components. As previously discussed, spectral crowding in the coffee matrix hampers the signal identification for dilute solutes.

Detection and quantification of aromatic species at low micromolar concentration requires, therefore, an excellent suppression of undesired signals originating from more concentrated components (up to 1000-fold). Here, we have devised an NMR-based chemosensor that reveals analyte association to the receptor by NMR signals in the hydride region of the 1H spectrum, generally free from background contributions. For each species associating to the iridium center, the chemosensor response consists of a pair of hyperpolarized hydride lines (“A” and “X” in complex (1)) in the NMR spectrum. Thanks to the p-H₂ derived hydride signal enhancement (up to 1000-fold increase compared to NMR at thermal equilibrium), it is possible to lower the detection limits of this NMR chemosensor to submicromolar concentrations. The spectrum in Figure 2A, recorded in a few minutes, shows several hydrides signals well above the noise threshold. The strength of NMR chemosensing is evident when several different analytes associate to the receptor: every substrate molecule binding to the iridium center is revealed by different spectral lines, thanks to the sensitivity of chemical shifts to the structure of complex (1). In principle, identification (and quantification) of the species bound to the iridium complex could be performed by titrating a given compound in the coffee extract and following the signal increase of the corresponding hydride(s). However, this method proves impractical in the present case, due to the overlap of the hydride resonances, as clearly illustrated inside the boxed region of the spectrum in Figure 2A. We have previously shown that high field continuous hyperpolarization via p-H₂ offers also the possibility
to acquire 2D correlation spectra with enhanced sensitivity between hydrides and aromatic protons. Similarly, the 2D SEPP-HoSQC experiment employed here provides an efficient tool to separate overlapping signals from different substrates, as evidenced by the plot in Figure 2B. Note that all correlations in the 2D spectrum appear as doublets because of the $J_{\text{AX}}$ scalar coupling between the two hydrides in complex (1).

Assignment of the strongest 2D correlations, reported in Figure 2B, was obtained by spiking the coffee extract. In the presence of a large excess of mtz cosubstrate, the 2D signal integral depends linearly on the substrate concentration.\cite{15,24}

This allows the determination of the analyte concentration in the submicromolar concentration regime by standard addition. A few representative standard addition curves are shown in Figure 3.

The value of each analytic concentration (expressed in $\mu$M) can be obtained from the abscissa intercept of the corresponding linear standard-addition curve. An uncertainty in the concentration determination of ca. 5–10% is obtained from error propagation.\cite{16} The results of the standard addition experiments are compared in Table 1 with the concentration values (in ppm, see the Supporting Information) reported in the literature for comparable coffee samples. For most components an excellent agreement was found with the results obtained using different techniques (i.e., HPLC,\cite{42} SIDA-GC/MS\cite{44}).

### DISCUSSION

As demonstrated by previously reported research,\cite{18–22} NMR chemosensing can combine the high specificity of receptors with the sensitivity of NMR chemical shifts to molecular structure. This is particularly important in the analysis of complex mixtures in which several homologous species can associate to a receptor; in these cases, the response of an NMR-based chemosensor allows the identification and differentiation of the target analytes. This has been achieved also in the present work, with the quantitative determination of several substituted pyrazines and pyridines in methanol extracts of ground coffee.

So far, NMR-based chemosensing has been realized following two different approaches, i.e. either selectively detecting the signals of the analytes of interest\cite{21,22} or measuring the variation of some NMR properties of the receptor upon association with the target.\cite{15,20} A recent implementation of the former approach relied on the combination of different highly selective NMR tools (i.e., diffusion filters,\cite{46} NOE and relaxation filters\cite{45}) to reveal the weak association of primary amines to gold nanoparticles coated with receptor units, while discarding background signals.\cite{22} The detection limit for such chemosensors, determined by the lowest measurable NMR response, is estimated to be in the submillimolar concentration range.

Alternatively, NMR-based chemosensors have been realized such that analyte binding is signaled by chemical shift changes for specific resonances of the receptor.\cite{18,20} Being virtually free from background interferences, $^{19}$F or $^{129}$Xe nuclear spins offer maximum sensitivity to probe the ligand–receptor association. Furthermore, the high sensitivity of $^{19}$F or $^{129}$Xe nuclear shifts to the local environment results in detectable changes in the NMR spectra upon analyte association to the receptor. Notably, nuclear spin hyperpolarization was used for the $^{129}$Xe NMR-based chemosensor to maximize the sensitivity.\cite{20} However, the small $^{129}$Xe chemical shift changes observed upon binding of the target analytes to the receptor has so far determined a detection limit in the submillimolar range, despite the high signal-to-noise ratio of the NMR spectrum.

Here, we follow a different strategy, by detecting $^1$H chemical shifts from both the receptor (the hydrides) and the bound analyte in a 2D correlation spectrum. In the absence of analytes, the receptor (i.e., the iridium center) is fully complexed by the cosubstrate mtz. In this case, the two hydrides are chemically equivalent, and no signal is obtained from the SEPP-based NMR experiments displayed in Figures 1B and 1C. Only upon association of an analyte to the receptor (by displacement of a mtz ligand), hyperpolarized hydride signals can be observed. Our method relies, therefore, on the detection of an NMR signal, rather than on a chemical shift change, to reveal association to the receptor. As a consequence, the large signal enhancement provided by $p$-$H_2$ derived hyperpolarization results in a drastic reduction of the detection limits to low-micromolar concentrations.

2D NMR spectra have been previously employed for quantitative determination of analytes in solution.\cite{45} However, in the case of hyperpolarization NMR spectra, a quantitative data analysis requires some caution, as previously discussed;\cite{16} a comparison of the 2D signal integrals of hyperpolarized samples can provide only a semiquantitative estimate of the relative concentrations, even in the present case with most of the analytes being structurally homologous. However, by using calibration techniques such as the standard addition method, it is possible to determine absolute amounts, here of different flavor components in coffee. Our results are in very good agreement with previously reported data based on different techniques, which confirms the validity of the proposed NMR approach.

### CONCLUSIONS

We have presented a new implementation of NMR-based chemosensing that allowed the detection and quantification of pyridine and pyrazine derivatives in a methanol coffee extract. Using NMR for signaling the receptor binding is particularly important for complex mixtures in which several target molecules are present. As shown in the present application, the sensitivity of chemical shifts to molecular structure allows a straightforward discrimination of the analytes bound to the receptor.

In general, the detection limit of NMR chemosensors is determined by the intrinsic (in)sensitivity of the technique. Recent implementations of NMR chemosensing for chemical analysis report such limit in the submillimolar range.\cite{20,22} Here, interaction with the receptor, an iridium complex, in the presence of $p$-$H_2$, results in approximately 1000-fold amplification of the NMR response. As a consequence, a

### Table 1. Analytes Concentration in Roasted Coffee Derived from Standard Addition

<table>
<thead>
<tr>
<th>analyte</th>
<th>concn (mM)</th>
<th>concn (ppm)</th>
<th>reference concn (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-hydroxypropyridine</td>
<td>273.7 ± 24.4</td>
<td>138.4 ± 14.0</td>
<td>140–400</td>
</tr>
<tr>
<td>pyridine\cite{54,48}</td>
<td>80.0 ± 3.1</td>
<td>31.2 ± 1.3</td>
<td>49–204</td>
</tr>
<tr>
<td>pyrazine\cite{45}</td>
<td>15.9 ± 0.6</td>
<td>6.3 ± 0.3</td>
<td>5.6–12.6</td>
</tr>
<tr>
<td>2-methylpyrazine\cite{46}</td>
<td>82.5 ± 9.2</td>
<td>37.8 ± 4.2</td>
<td>34.8–70.6</td>
</tr>
<tr>
<td>2-ethylpyrazine\cite{45}</td>
<td>23. ± 2.1</td>
<td>11.7 ± 1.1</td>
<td>4.1–9.0</td>
</tr>
<tr>
<td>2,6-dimethylpyrazine\cite{45}</td>
<td>33.7 ± 1.4</td>
<td>17.3 ± 1.0</td>
<td>14.3–24.6</td>
</tr>
</tbody>
</table>

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Oligopeptides that can be hyperpolarized by weakly bio
determination of these compounds in complex mixtures such as
chem.6b00184. such as nucleobases,23,50 amino acids,51 drugs,52,53 and tagged
nitrogenous heterocyclic compounds, such as pyridine and
occurs via a nitrogen lone pair, which makes several
receptor. In almost all cases reported so far, this binding
excellent agreement was found. The proposed chemosensor
from di
obtained absolute concentrations with reported values derived
REFERENCES

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ABBREVIATIONS

p-H2 parahydrogen
mtz 1-methyl-1,2,3-triazole

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