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1 **Intramolecular non-covalent isotope effects at natural abundance associated with**  
2 **the migration of paracetamol in solid matrices during liquid chromatography**

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21 **Abstract**

22 Position-specific isotope analysis by Nuclear Magnetic Resonance spectrometry was employed to  
23 study the  $^{13}\text{C}$  intramolecular isotopic fractionation associated with the migration of organic  
24 substrates through different stationary phases. Liquid chromatography is often used to isolate  
25 compounds prior to their isotope analysis and this purification step potentially alters the isotopic  
26 composition of target compounds introducing a bias in the later measured data. Moreover,  
27 results from liquid chromatography can yield the sorption parameters needed in reactive  
28 transport models that predict the transport and fate of organic contaminants to in the  
29 environment. The aim of this study was to use intramolecular isotope analysis to study both  $^{13}\text{C}$   
30 and  $^{15}\text{N}$  isotope effects associated with the migration of paracetamol through different stationary  
31 phases and to compare them to effects observed previously for vanillin. Results showed very  
32 different intramolecular isotope fractionation profiles depending on the chemical structure of the  
33 stationary phase. The data also demonstrate that both the amplitude and the distribution of  
34 measured isotope effects depend on the nature of the non-covalent interactions involved in the  
35 migration process. Results provided by theoretical calculation performed during this study also  
36 confirmed the direct link between observed intramolecular isotope fractionation and the nature  
37 of involved intermolecular interactions. It is concluded that the nature of the stationary phase  
38 through which the substrate passes has a major impact on the intramolecular isotopic  
39 composition of organic compounds isolated by chromatography methods. These findings allow  
40 to better understand the fate of organic contaminants undergoing reactive transport in soils or  
41 aquifers.

42

43 **Keywords:**

44 Position-specific isotope effects – isotope enrichment factor – migration – paracetamol – Rayleigh  
45 equation – irm-<sup>13</sup>C NMR– DFT calculations

46

## 47 **1. Introduction**

48 Liquid chromatography, commonly used to isolate compounds from a complex mixture, is  
49 known to create isotope effects. The non-covalent interactions settled between the solid phase  
50 and the substrate during the migration are isotopically selective resulting in isotopic fractionation  
51 of the migrating compounds. The link between these interactions and the associated non-  
52 covalent isotope effects (NCIEs) remains poorly documented [1–3]. Understanding the isotopic  
53 fractionation processes associated with chromatography is of primary importance for correcting  
54 further isotopic measurements when used during the sample preparation and/or the direct  
55 coupling of isotope ratio monitoring by Mass Spectrometry (irm-MS, known also as IRMS: Isotope  
56 Ratio by Mass Spectrometry) with high-performance liquid chromatography (HPLC) [4] or gas  
57 chromatography (GC) [5,6]. Moreover, liquid chromatography (and more generally sorption  
58 experiments) are used for modeling the migration of organic compounds in environment to  
59 determine the impact of this process on considered pollutants isotopic composition and to study  
60 their origins and fate [7,8].

61 It is difficult to study migration mechanisms and understand their associated isotope  
62 fractionations of a pollutant in environment studies, as example. Indeed, this phenomenon  
63 involves different processes such as advection, diffusion/dispersion and sorption. Advection

64 refers to the transport of a compound depending on the ground relief or the presence of a stream  
65 (air, water) in the considered polluted site. It corresponds to the movement of a contaminant  
66 plume in the soil or in water) and does not depend on the chemical composition, so it is  
67 considered as inert in terms of isotope fractionation. Diffusion and dispersion define the way a  
68 contaminant will spread in the environment and may contribute to isotope fractionation.  
69 However, these fractionations are considered to be small or non-significant in advection-  
70 dominated transport situations and for experiments with short durations [9–11]. By contrast, the  
71 sorption/desorption processes occurring during the migration directly involve intermolecular  
72 non-covalent interactions, which have already been proven to be associated with intramolecular  
73  $^{13}\text{C}$  isotope effects, i.e. position-specific  $^{13}\text{C}$  fractionation [12]. Furthermore, different types of  
74 intermolecular interactions (hydrogen bonds, van der Waals,  $\pi$ -stacking, halogen bonds) can be  
75 observed during migration depending on the molecular structures of both the contaminant and  
76 the solid matrix resulting in variable isotope effects.

77 The isotope fractionations and the calculation of the associated isotopic effects provide  
78 information on the intensity of interactions between the solute and the solid matrix. Most  
79 isotope studies are performed using irm-MS targeting mostly  $^{13}\text{C}$  and  $^2\text{H}$  in organic contaminants  
80 [8,13] and moreover on enriched material for the chromatography investigations [1–3]. However,  
81 this method only provides a measurement of the average isotopic composition, which is the mean  
82 value of isotope ratios of all carbon or hydrogen positions within the considered molecule. Using  
83 this method, isotopologues (two molecules with a different number of heavy atoms, see section  
84 3.1 for further definition) that react differently with the considered stationary phase will elute  
85 separately [14]. Fully deuterated compounds can be separated from their protiated counterparts

86 by liquid [3] or gas chromatography [15], for example. To access the intramolecular  $^{13}\text{C}$   
87 information without prior (bio)chemical degradation of the target compound, a small number of  
88 position-specific isotope analysis (PSIA) techniques have been developed such as isotope ratio  
89 monitoring by  $^{13}\text{C}$  Nuclear Magnetic Resonance (irm- $^{13}\text{C}$  NMR) [16–18], on-line pyrolysis coupled  
90 with irm-MS [19–22] and high-resolution irm-MS [23,24]. All these techniques make it possible to  
91 identify which isotopomer (two molecules with the same amount of heavy atom but located on  
92 different position) preferentially interacts during the studied process [14]. PSIA using irm- $^{13}\text{C}/^{15}\text{N}$   
93 NMR has been successfully used to reveal intramolecular NCIE during chromatographic elution  
94 on normal phase for  $^{13}\text{C}$  [12,25] and  $^{15}\text{N}$  [26] or inverse phase for  $^{13}\text{C}$  [27]. Furthermore, this  
95 approach was able to found a possible link between the magnitude of fractionation and the  
96 strength of intermolecular interactions within a liquid during the liquid-vapor transition as  
97 evaporation of VOCs for  $^{13}\text{C}$  [28,29] or distillation for  $^2\text{H}$  and  $^{13}\text{C}$  [14,30].

98 In the present study,  $^{13}\text{C}$  intramolecular isotope analysis using irm- $^{13}\text{C}$  NMR was employed to  
99 observe the position-specific isotope effects (PSIEs) associated with the chromatographic elution  
100 on several stationary phases. The potential connection between the magnitude of fractionation  
101 and strength of interaction between organic solute and solid phase is expected to provide insights  
102 about how different types of matrices could retain organic chemicals. Isotope fractionation  
103 associated with migration of organic contaminants were largely studied using deuterated  
104 compounds [1–3]. However, only few works looked at isotopes at natural abundance and the  
105 influence of migration on isotope composition is still debated. As an example, the migration of  
106 BTEX (Benzene, Toluene, Ethylbenzene, Xylenes) on reverse phase HPLC did not show any  
107 significant IE for  $^{13}\text{C}$  at the global level [31], nor did the migration of BTEX and MTBE on HPLC

108 using humic acid as stationary phase [32]. Some sorption experiments of BTEX and chlorinated  
109 solvents on activated charcoal also showed non-significant IEs for global  $^{13}\text{C}$  and  $^2\text{H}$  compositions  
110 [33,34]. Nevertheless, some other experiments highlighted the presence of  $^{13}\text{C}$  and  $^2\text{H}$  isotope  
111 fractionation during sorption/desorption cycles of BTEX on different adsorbing materials, still  
112 using average isotope parameters [35], which encouraged us to undertake further experiments  
113 probing PSIA because the small detected IEs may be composed by counteractive normal and  
114 inverse IEs within the studied molecules resulting in the measurement of low or non-significant  
115 global isotope effects, i.e. using irm- $^{13}\text{C}$  MS. The concomitance of normal and inverse isotope  
116 effects within the same molecule was already detected during the migration of vanillin and  
117 derivatives on both normal phase silica gel (SG) and reverse phase (RP) [12,25]. The results of  
118 these works were presented as a qualitative description of the  $^{13}\text{C}$  intramolecular fractionations  
119 observed, with no enrichment factor calculated. Although, isotope fractionation of vanillin  
120 migrating on RP was further studied to develop a reactive transport capable of predicting the  
121 position-specific isotopic fractionation behavior of this compound in the environment [27].

122 As soil composition is very variable and not homogeneous, we have chosen to study the migration  
123 of paracetamol through different pure materials using liquid chromatography and to measure  
124 associated intramolecular  $^{13}\text{C}$  and  $^{15}\text{N}$  IEs. Four model materials with various chemical  
125 compositions were used as stationary phase in this study: silica gel normal phase (SG), cellulose  
126 (CE), activated charcoal (AC) and silica gel C8-reversed phase (RP). The choice of the solute and  
127 these solid matrices will be further rationalized in the section 3, as well the role of the eluent that  
128 is important in the selection of the isotopomers during the elution [1–3]. Thus, it is expected that  
129 different types of non-covalent intermolecular interactions contribute in the PSIF. The

130 determination of the enrichment factor at each carbon position should help in the evaluation of  
131 the strength of these interactions. That is the reason why we have performed these calculations  
132 from previous published data of vanillin eluted through normal phase silica gel [12] and reversed  
133 phase silica gel [27] to better highlight the role of non-covalent interactions in intramolecular  
134 isotope fractionations occurring during the migration. In addition, quantum mechanical  
135 calculations for the transition of paracetamol from diethyl ether (low polarity) to acetone  
136 (moderate polarity) or water (polar compound) were performed during this study. These  
137 theoretical data should help better understanding the effect of hydrogen-bonding and, more  
138 generally, the polarization on measured PSIEs associated with the migration.

139

## 140 **2. Materials and Methods**

### 141 *2.1. Chemicals*

142 Paracetamol ( $C_8H_9NO_2$ , CAS-Number 103-90-2), silica gel high-purity grade, average pore size 60  
143 Å (52-73 Å), 70-230 mesh, 63-200 µm, silica gel C8-reversed phase, and activated charcoal were  
144 purchased from Sigma Aldrich. Cellulose was obtained from Fluka-chemicals and DMSO- $d_6$  was  
145 purchased from Eurisotop. Acetone and diethyl ether used as eluent were from Sigma Aldrich as  
146 HPLC quality, without further purification.

### 147 *2.2. Chromatographic procedures*

148 In order to determine both  $^{13}C$  and  $^{15}N$  isotope fractionation occurring during the migration of  
149 paracetamol through different materials, liquid chromatography experiments were performed  
150 using 4 different stationary phases (separately): normal phase silica gel (SG), silica gel C8-reversed



151 phase (RP), cellulose (CE) and activated charcoal (AC). For each experiment the amount of  
152 material was adapted in order to obtain around 250 mm of stationary phase in a chromatography  
153 column (internal diameter 40 mm except for silica gel C8-reversed phase which was 30 mm). Then  
154 the protocol was the same for all types of stationary phase: (i) 2 g of pure paracetamol was  
155 introduced as a powder at the top of the column and gently mixed with the first 20 mm of the  
156 stationary phase to start the migration; (ii) The elution was performed using a mixture of 90% of  
157 diethyl ether and 10% acetone, as acetone solubilizes well paracetamol to some extent [36],  
158 while it is almost totally non-soluble in ether that is used to decrease the polarity of acetone,  
159 avoiding thus, a too rapid elution of paracetamol and (iii) it was collected in 4 fractions (approx.  
160 500 mg each). The exact amount of each fraction was determined by weighting the eluted  
161 paracetamol after evaporation of the solvents to dryness and the corresponding percentage of  
162 introduced paracetamol was calculated (see Table 2). The starting paracetamol and the 4 samples  
163 obtained from elution of each stationary phase chromatography were analyzed for their isotopic  
164 parameters.

### 165 *2.3. Global <sup>13</sup>C and <sup>15</sup>N isotope analysis*

166 Carbon (<sup>13</sup>C/<sup>12</sup>C) and nitrogen (<sup>15</sup>N/<sup>14</sup>N) global isotope ratio measurements, expressed in delta  
167 notation ( $\delta^{13}\text{C}_g$  and  $\delta^{15}\text{N}_g$  (‰)), were determined by irm-MS using an Integra2 spectrometer  
168 (Sercon Instruments, Crewe, UK) linked to a Sercon elemental analyzer (EA) fitted with an  
169 autosampler (Sercon Instruments, Crewe, UK). About 1 mg of sample was sealed in a tin capsule.  
170  $\delta^{13}\text{C}_g$  and  $\delta^{15}\text{N}_g$  of the resulting gases, CO<sub>2</sub> and N<sub>2</sub> were determined by reference to a working  
171 standard of glutamic acid standardized against calibrated international reference material (IAEA-

172 CH6 and IAEA-CH7 for carbon isotope ratio and IAEA-N1 and IAEA-N2 for nitrogen isotope ratio).

173 The  $^{13}\text{C}$  and  $^{15}\text{N}$  global isotope compositions of the whole molecule were calculated from:

174 
$$\delta^{\text{A}}\text{X} (\text{‰}) = \left( \frac{R}{R_{\text{Std}}} - 1 \right) \times 1000 \quad \text{eq. 1}$$

175 Where  $^{\text{A}}\text{X}$  stands for either  $^{13}\text{C}$  or  $^{15}\text{N}$ ,  $R$  is the isotope ratio of the sample and  $R_{\text{Std}}$  is the isotope  
176 ratio of Vienna Pee Dee Belemnite reference standard (V-PDB) for  $^{13}\text{C}$  ( $R_{\text{Std}} = 0.0112372$ ) or  
177 atmospheric air for  $^{15}\text{N}$  ( $R_{\text{Std}} = 0.003677$ ).

#### 178 *2.4. Intramolecular $^{13}\text{C}$ isotope analysis by irm- $^{13}\text{C}$ NMR*

179 PSIA of paracetamol using irm- $^{13}\text{C}$  NMR was described in a previous study [37]. The sample  
180 preparation consisted in the successive addition in a 4 mL vial of 250 mg of paracetamol and 600  
181  $\mu\text{L}$  of  $\text{DMSO-}d_6$ . The respective amount of each was adapted according to (i) the T1 values  
182 (longitudinal relaxation), (ii) the solubility in the deuterated solvent and (iii) the  $^{13}\text{C}$  NMR  
183 spectrum: no peak overlapping (see Figure S3). Irm- $^{13}\text{C}$  NMR spectra were recorded using an  
184 AVANCE I 400 spectrometer (Bruker Biospin, Wissembourg, France), fitted with a 5 mm i.d.  $^1\text{H}/^{13}\text{C}$   
185 dual<sup>+</sup> probe, carefully tuned at the recording frequency of 100.61 MHz. The temperature of the  
186 probe was set to 303 K, without tube rotation. The exact NMR acquisition conditions are detailed  
187 in the SI. Isotope  $^{13}\text{C}$  compositions were calculated from processed spectra as described  
188 previously [38]: further details are given in the SI (Table S2).

#### 189 *2.5. Calculation of enrichment factors ( $\varepsilon$ ) and associated expanded uncertainty ( $U$ )*

190 Enrichment factors ( $\varepsilon$  in ‰) is a common way used to express IEs. An isotope effect is considered  
191 as normal (light isotopologues respond preferentially) when  $\varepsilon < 0$  and inverse when  $\varepsilon > 0$ .

192 Enrichment factors were determined using Rayleigh plots in which  $\ln(f)$  is plotted on the x-axis  
193 (where  $f$  is the fraction of paracetamol remaining in the column) and  $\ln(R/R_0)$  on the y-axis (eq. 2  
194 and 3,  $R$  is the isotope ratio of the sample and  $R_0$  the isotope ratio of paracetamol at  $t_0$ ) [39,40].

$$195 \ln\left(\frac{R}{R_0}\right) = (\alpha - 1) \times \ln(f) \quad \text{eq. 2}$$

$$196 \varepsilon = (\alpha - 1) \times 1000 \quad \text{eq. 3}$$

197 In Rayleigh plots, the slope of the trend line corresponds to the enrichment factor ( $\varepsilon$ ) and the  
198 associated root mean square ( $R^2$ ) gives a first indication of the quality of the linearity. However,  
199 in order to determine the significance threshold of the enrichment factor, the expanded  
200 uncertainty needs to be calculated. The determination of the expanded uncertainty associated  
201 with the enrichment factor determined using the Rayleigh-plot can be directly calculated using  
202 the function "LINEST" in Microsoft Excel™, as previously described [39,41]. This function  
203 calculates both the slope and the standard deviation of the trend line (STDV slope). The expanded  
204 uncertainty can thus be calculated as follows (eq. 4):

$$205 U = k \times \text{STDV slope} \quad \text{eq. 4}$$

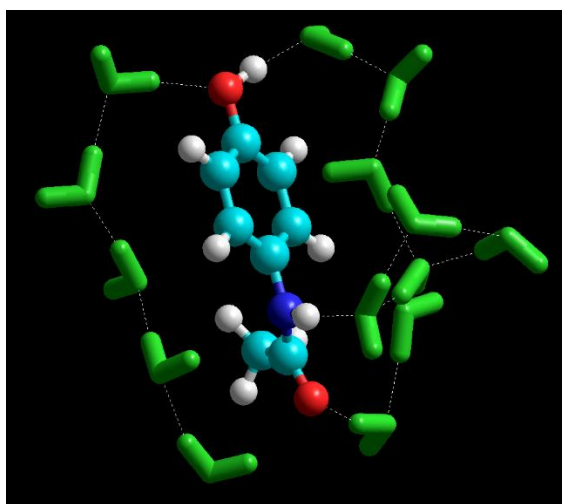
206 where  $k = 2$  for a coverage factor at the 95% confidence level according to Student's  $t$ -distribution.

207 In this context, data are presented as  $\varepsilon \pm U$  and enrichment factors are considered as significant  
208 when  $|\varepsilon| > U$ .

### 209 *2.6. Theoretical calculation of enrichment factors ( $\varepsilon$ )*

210 We have used two models of the environment. The first one involved a SMD continuum solvent  
211 model [42], which uses bulk properties of the solvent to create a dielectric cavity in which the

212 solute is immersed. In the second approach, explicit solvent molecules are used. Within this  
213 approach we have used 14 water molecules comprising the first solvation shell of paracetamol  
214 (see Figure 1) as a model of well-defined, strong hydrogen bonding network with availability of  
215 both proton donor and proton acceptor sites. Calculations were carried out at the DFT level of  
216 theory, using  $\omega$ B97X-D functional [43] expressed in the def2-TZVP basis set [44] as implemented  
217 in the Gaussian16 program [45], which proved successful in our recent studies on vapor pressure  
218 isotope effects of ethanol [46].



219

220 **Figure 1:** Solvent network around paracetamol molecule.

221 We have carried out calculations for structures of paracetamol in the gas phase, continuum  
222 solvent models of diethyl ether and acetone, and surrounded by 14 explicitly treated water  
223 molecules. For the optimized structures frequency calculations were carried out to ensure they  
224 represent local minima, and for calculations of isotope effects (which were subsequently  
225 converted into isotopic enrichment factors) using the Isoeff program [47].

226

## 227 **3. Results and Discussion**

### 228 *3.1. Design of the experiments: choices of solid phases and solute*

229 The goal of the work being double: (i) relationship between the type of stationary phase and the  
230 NCIE for a given chemical in liquid chromatography; and (ii) contribution to modelling the isotope  
231 fractionation upon migration of organic chemicals in a soil, the choice of the solid matrices and  
232 of the solute should be further explained. The relationship between structural substitutions and  
233 NCIE during the chromatographic elution on normal phase silica gel of a group of phenolic  
234 compounds related to vanillin was previously investigated on qualitative basis [12,25]. Herein one  
235 compound has been studied during elution on four stationary phases. This compound is  
236 paracetamol also called acetaminophen, it is one of the most widely used drugs in the world.  
237 Although this painkiller is a prodrug, which means that it needs to be partially metabolized in the  
238 liver to become active [48], large quantities of this whole molecule are found in the environment.  
239 Paracetamol can be converted into *N*-acetyl-*p*-benzoquinone imine and 1,4-benzoquinone in  
240 wastewater treatment plants by reacting with hypochlorite ions ( $\text{ClO}^-$ ) [49]. These compounds are  
241 suspected to be genotoxic and mutagenic, so the monitoring of the fate of paracetamol is of  
242 primary importance [50–52].

243 Because of a high complexity, the NCIE during migration of paracetamol into a soil would difficult  
244 to interpret as the different sources of interaction nor their strengths between the chemical and  
245 the solid phase could be described. We opted to a differentiation of each category of forces  
246 responsible of the retention (or not) during the elution. As such, normal phase silica gel (SG) is  
247 both polar and hydrogen bond provider (silanol groups), cellulose is much less polar but still

248 provides hydrogen bonds (hydroxyl groups), the reverse C8 phase (RP) may be considered as  
249 nonpolar and will favor weak forces (van der Waals), and finally the charcoal is well known to sorb  
250 chemicals via  $\pi$ -ring current interactions. This diversity of dominating interactions for the studies  
251 solid phases allowed us additionally to get a deeper insight into theoretical modelling of isotopic  
252 fractionations using quantum-mechanical calculations.

253 The nature of the eluent is recognized as contributing to the elution order of the isotopomers. All  
254 the studies of the isotope fractionation pointed out that the composition of solvents can change  
255 the interactions between the solute and the solid phase. For the present work, the eluent has  
256 been fixed at 10% of acetone and 90% of diethyl ether and the same for all experiments and  
257 therefore for the four stationary phase. Paracetamol is not very soluble in all organic solvents and  
258 is preferentially in alcohols. But the presence of strong hydrogen bonds via the hydroxyl groups  
259 could annihilate other weak interactions. It is then expected that the isotope fractionation due to  
260 weak interactions between paracetamol and the stationary phase could be observed. The mixture  
261 of acetone (10%) and diethyl ether (90%) is polar enough to allow a chromatographic experiment  
262 for the four solid phases with a gradual migration of paracetamol. Finally, being very volatile,  
263 these solvents can be easily removed for each collected fraction leaving dry paracetamol for  $^{13}\text{C}$   
264 NMR.

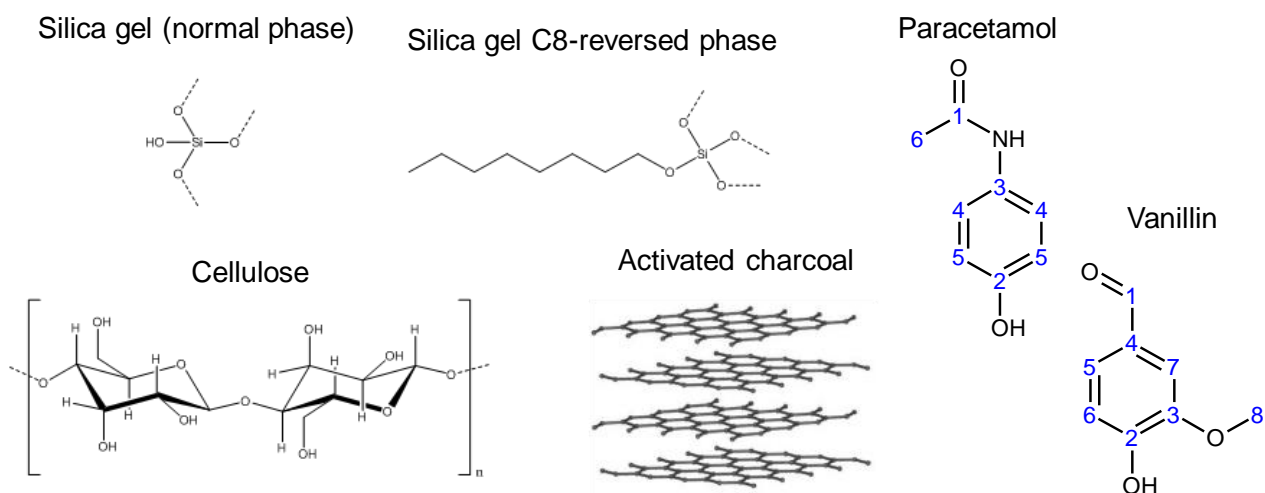
### 265 *3.2. What is measured by irm- $^{13}\text{C}$ NMR and repeatability of the isotope compositions*

#### 266 *3.2.1 Data obtained from isotopic NMR*

267 Even if several papers are now available in the literature [18,38,53], we think that it is worthwhile  
268 to further describe the irm- $^{13}\text{C}$  NMR methodology and the data it provides. Any molecules

269 containing isotopes are isotopologues, *i.e.* they have the same constitution and same  
 270 configuration but differ in their isotope substitutions. Quantifying isotopologues having two or  
 271 more heavy isotopes is not accessible for  $^{13}\text{C}$  and  $^{15}\text{N}$ , due their very low abundance, by current  
 272 routine techniques as irm-MS or irm-NMR: the mono labelled, at natural abundance, molecules  
 273 are considered. These molecules are named isotopomers, *i.e.* same chemical structure in which  
 274 the heavy isotope differs as to its position in the structure. PSIA is therefore the approach  
 275 consisting in the determination of the profile of isotopomers, as opposed to the quantitation of  
 276 the mean ratio (bulk or global) of the  $^{13}\text{C}$  isotopologues versus the light one ( $^{12}\text{C}$ ). Irm- $^{13}\text{C}$  NMR  
 277 resolves fractionation of natural isotope values in  $^{13}\text{C}$  for every position in the target molecules.  
 278 For low isotopic abundance, as for natural-abundance  $^{13}\text{C}$  (1.08%), molecules containing more  
 279 than one  $^{13}\text{C}$  are usually not detected by NMR. Therefore, each chemical shift (that is the peak in  
 280 the spectrum, named *i*) corresponds to an isotopomer *i* (mono-labelled at natural abundance).  
 281 Paracetamol has 8 carbon atoms at 6 specific positions (then 6  $^{13}\text{C}$  isotopomers numbered as  
 282 described in Figure 2), and one nitrogen atom.

283



285 **Figure 2:** General chemical structure of the stationary phases employed in the present study. Also  
 286 shown are the molecular structures of paracetamol and vanillin with the carbon atoms numbered  
 287 in relation to decreasing  $^{13}\text{C}$  chemical shift in the  $^{13}\text{C}$  NMR spectrum.

288  
 289 The area  $S$  of the corresponding signal in the NMR spectrum is directly proportional to the amount  
 290 of this isotopomer. The relationship between the mean and the position-specific  $^{13}\text{C}$  content is  
 291 found at the isotopic abundance  $x$  level:  $x_i = x_g \cdot f_i / F_i$  (Table 1). Thus irm- $^{13}\text{C}$  NMR gives access to  
 292 the relative intramolecular  $^{13}\text{C}$  distribution, while irm-MS reports on the total amount of  $^{13}\text{C}$   
 293 isotopes. Further details on the calculation of  $\delta^{13}\text{C}_i$  are given in the SI.

294

295 **Table 1:** Symbols and their definitions used in the present work.

Symbol	Definition
$\delta^{13}\text{C}$	Carbon isotope composition: carbon isotopic ratio of the molecule relative to the international standard (Vienna Pee Dee Belemnite V-PDB)
$\delta^{13}\text{C}_g$	$^{13}\text{C}$ mean isotopic composition of a whole molecule measured by irm-MS: global $^{13}\text{C}$ content. Also found as $\delta^{13}\text{C}_b$ for bulk value, or $\delta^{13}\text{C}_T$ for total value
$\delta^{13}\text{C}_i$	$^{13}\text{C}$ isotopic composition of the carbon position $i$ measured by PSIA (as irm- $^{13}\text{C}$ NMR in this work)
$\Delta\delta^{13}\text{C}_g$	Difference between final $\delta^{13}\text{C}_g$ and initial $\delta^{13}\text{C}_g$
$\Delta\delta^{13}\text{C}_i$	Difference between final $\delta^{13}\text{C}_i$ and initial $\delta^{13}\text{C}_i$
$f_i$	Molar fraction for a carbon site $i$ measured by irm- $^{13}\text{C}$ NMR = area $S$ of the peak corresponding to the carbon position $i$ ( $S_i$ ) divided by the sum of all the carbon sites of the molecule: $f_i = \frac{S_i}{\sum_n S_i}$ .



$F_i$	Statistical molar fraction for a carbon site $i$ : molar fraction for the carbon site $i$ in cases of homogeneous $^{13}\text{C}$ distribution within the molecule (example: $F_1 = 1/8$ for paracetamol)
$f_i/F_i$	Reduced molar fraction for a carbon $i$ : any shift from 1 indicates an isotope fractionation
$x$	Isotopic abundance
$\epsilon_g$	Enrichment factor calculated as described in the experimental section from $\Delta\delta^{13}\text{C}_g$
$\epsilon_i$	Enrichment factor calculated as described in the experimental section from $\Delta\delta^{13}\text{C}_i$

296 Note:  $^{15}\text{N}$  has only one possible position in paracetamol so only global analysis (irm- $^{15}\text{N}$  MS) is  
 297 done.

### 298 3.2.2 Precision of the isotopic compositions

299 The repeatability of both intramolecular and global isotope analysis was investigated. Data  
 300 presented in Table 2 show a standard deviation (SD) of isotopic composition measurements  
 301 comprised between 0.1 and 0.7‰. More interesting, global and intramolecular isotope  
 302 compositions of material used as working reference were calculated using data from all collected  
 303 fractions and the differences between these calculated values and direct measurements on the  
 304 reference materials were calculated (see Table 2). These differences are comprised between 0.1  
 305 and 1.2‰ which confirms the repeatability and reproducibility of the isotope measurements (irm-  
 306 EA/MS and irm- $^{13}\text{C}$  NMR). Moreover, these data prove that differences in PSIEs discussed in this  
 307 article are directly associated with the migration experiments and are not due to measurement  
 308 error or a lack of recovery of the migrating material.

309

310 **Table 2:** Repeatability study of  $\delta^{13}\text{C}_g$ ,  $\delta^{15}\text{N}_g$  by irm-MS and intramolecular  $^{13}\text{C}$  distribution  
 311 measurements in paracetamol by irm- $^{13}\text{C}$  NMR,  $\delta^{13}\text{C}_i$  (SD = standard deviation), expressed in ‰.  
 312 Also shown, the isotopic composition of material used as working reference calculated from  
 313 values measured on the different fractions (see calculated) and the absolute difference with the  
 314 direct measurement of paracetamol (see |difference|).

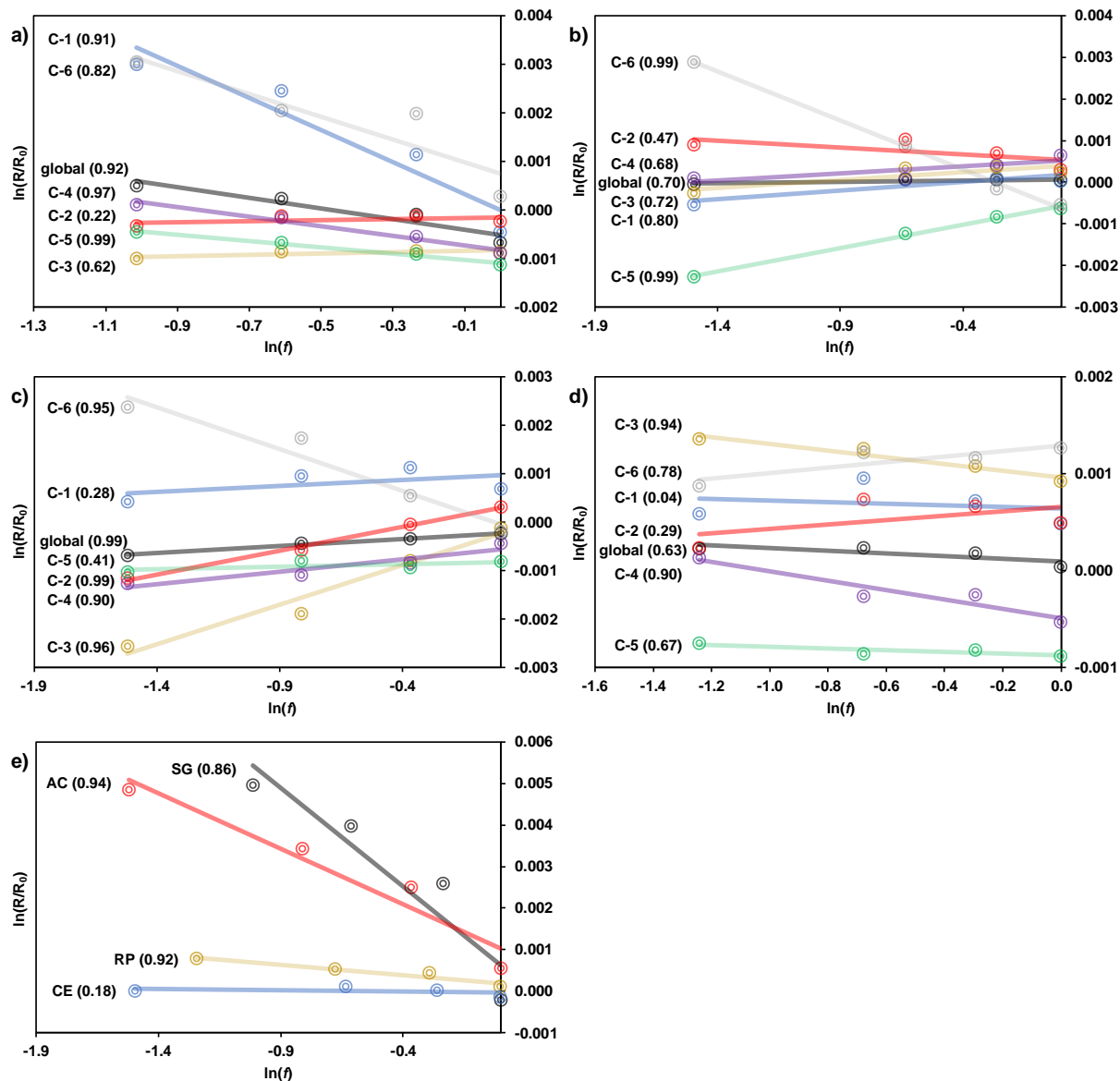
Experiment	$\delta^{13}\text{C}$ (‰)							$\delta^{15}\text{N}_g$ (‰)	
	global	C-1	C-2	C-3	C-4	C-5	C-6		
1	-26.9	-32.4	-27.9	-34.9	-22.8	-21.6	-31.1	-3.7	
2	-26.9	-31.8	-26.3	-35.2	-23.1	-22.3	-31.2	-3.7	
3	-26.9	-31.6	-27.6	-34.1	-22.8	-22.0	-32.4	-3.8	
4	-26.9	-31.1	-26.9	-35.0	-22.9	-22.2	-32.1	-3.7	
5	-27.0	-32.3	-26.5	-34.5	-22.7	-22.7	-31.2	-3.7	
mean	-26.9	-31.9	-27.0	-34.7	-22.9	-22.2	-31.6	-3.7	
SD	0.1	0.5	0.7	0.4	0.2	0.4	0.6	0.1	
SG	calculated	-27.6	-32.9	-28.1	-35.7	-23.7	-22.7	-30.9	-3.9
	difference	0.6	0.4	0.2	0.8	0.9	1.1	0.3	0.2
CE	calculated	-26.9	-32.4	-27.6	-34.7	-22.2	-22.3	-31.7	-3.9
	difference	0.0	0.0	0.3	0.2	0.6	0.6	0.5	0.1
AC	calculated	-27.1	-31.8	-27.6	-35.0	-23.2	-22.5	-31.3	-3.2
	difference	0.2	0.7	0.3	0.1	0.4	0.8	0.2	0.5
RP	calculated	-26.9	-32.0	-27.4	-34.0	-23.3	-22.5	-29.9	-3.6
	difference	0.0	0.5	0.5	0.9	0.5	0.9	1.2	0.1

315

316 3.3.  $^{13}\text{C}$  and  $^{15}\text{N}$  isotope effects

317 For each of the four migration experiments, global and  $^{13}\text{C}$  intramolecular (carbon positions 1 to  
318 6) data were plotted on the same graph in order to determine corresponding  $\epsilon$  values and  
319 nitrogen data are presented in a separated graph (see Figure 3). The Rayleigh equation and, by  
320 extension, Rayleigh plot are usually employed to follow the evolution of the isotope ratio of a  
321 compound as a function of a reaction's progress. This equation allows calculating the  
322 fractionation factor created by a considered process such as a (bio)chemical reaction [39] or the  
323 migration during liquid chromatography in the present work.

324



325

326 **Figure 3:** Rayleigh plots drawn using global and intramolecular (C-1 to C-6)  $^{13}\text{C}$  experimental data  
 327 for migration in (a) normal phase silica gel, (b) cellulose, (c) activated charcoal and (d) reversed  
 328 phase silica gel. (e) Rayleigh plots drawn for  $^{15}\text{N}$  data of the migration in each studied material  
 329 (SG: normal phase silica gel, CE: cellulose, AC: activated charcoal and RP: reversed phase silica gel.  
 330 Numbers in parentheses indicate the coefficient of determination ( $R^2$ ) of each trend-line.

332 Both  $^{13}\text{C}$  intramolecular and  $^{15}\text{N}$  enrichment factors measured during the migration of  
 333 paracetamol through the four studied stationary phases (silica gel = SG; cellulose = CE; activated  
 334 charcoal = AC and C8-reversed phase = RP) are presented in this section and summarized in Table  
 335 3. As detailed in section 2.5, isotope effects are considered as normal (molecules containing light  
 336 isotopes are preferentially eluted) when  $\varepsilon < 0$  and inverse (heavy isotopologues are less retained  
 337 in the column) when  $\varepsilon > 0$ .

338

339 **Table 3:** Enrichment factors ( $\varepsilon$  in ‰) obtained from irm-EA/MS (bulk) and from irm- $^{13}\text{C}$  NMR  
 340 (position-specific, C-1 to C-6) upon migration of paracetamol through the different solid phases  
 341 as described in experimental section (SG = silica gel; CE = cellulose; AC = activated charcoal and  
 342 RP = silica gel C8-reversed). The values shown after “ $\pm$ ” are the expanded uncertainties of (U in ‰).

	$\varepsilon$ (‰)							$\text{N}_{\text{bulk}}$
	$\text{C}_{\text{bulk}}$	C-1	C-2	C-3	C-4	C-5	C-6	
<b>SG</b>	$-1.1 \pm 0.5$	$-3.3 \pm 1.5$	$+0.1 \pm 0.3$	$+0.1 \pm 0.1$	$-1.0 \pm 0.2$	$-0.6 \pm 0.1$	$-2.3 \pm 1.6$	$-4.7 \pm 2.5$
<b>CE</b>	$+0.1 \pm 0.1$	$+0.4 \pm 0.3$	$-0.3 \pm 0.5$	$+0.4 \pm 0.3$	$+0.3 \pm 0.3$	$+1.1 \pm 0.1$	$-2.4 \pm 0.2$	$-0.1 \pm 0.2$
<b>AC</b>	$+0.3 \pm 0.0$	$+0.2 \pm 0.6$	$+1.0 \pm 0.1$	$+1.6 \pm 0.5$	$+0.5 \pm 0.3$	$+0.1 \pm 0.2$	$-1.7 \pm 0.6$	$-2.7 \pm 0.9$
<b>RP</b>	$-0.1 \pm 0.1$	$-0.1 \pm 0.5$	$+0.2 \pm 0.5$	$-0.3 \pm 0.1$	$-0.5 \pm 0.2$	$-0.1 \pm 0.1$	$+0.3 \pm 0.2$	$-0.5 \pm 0.2$

343

344 The link between observed IEs and the intermolecular interactions occurring between  
 345 paracetamol and each considered stationary phase is discussed using their chemical structures  
 346 described in Figure 2. In addition, previously published data obtained during the migration of

347 vanillin through SG [12] and RP [27] were treated using the method described in section 2.5 and  
348 summarized in Table 4 and were included in the discussion.

349  
350 **Table 4:** Enrichment factors ( $\epsilon$  in ‰) obtained from irm-EA/MS (bulk) and from irm- $^{13}\text{C}$  NMR  
351 (position-specific, C-1 to C-8) upon migration of vanillin through silica gel (SG, Botosoa *et al.* 2009)  
352 and reversed phase silica gel RP-18 (RP, Höhener *et al.* 2012). The values shown after “ $\pm$ ” are the  
353 expanded uncertainties of (U in ‰), at 95% confident level.

354

	$\epsilon$ (‰)								
	<b>C<sub>bulk</sub></b>	<b>C-1</b>	<b>C-2</b>	<b>C-3</b>	<b>C-4</b>	<b>C-5</b>	<b>C-6</b>	<b>C-7</b>	<b>C-8</b>
<b>SG</b>	-0.9 $\pm$ 0.1	-3.3 $\pm$ 0.6	+1.5 $\pm$ 0.4	-1.5 $\pm$ 0.2	-3.4 $\pm$ 0.2	-2.5 $\pm$ 0.4	+2.4 $\pm$ 0.3	-1.3 $\pm$ 0.2	-0.9 $\pm$ 0.1
<b>RP</b>	+0.3 $\pm$ 0.3	+0.6 $\pm$ 0.6	+1.1 $\pm$ 0.2	+0.7 $\pm$ 0.5	+0.4 $\pm$ 0.8	+0.3 $\pm$ 0.1	+0.3 $\pm$ 0.4	+0.2 $\pm$ 0.4	+0.3 $\pm$ 0.3

355

356

### 357 3.3.1. Normal phase silica gel (SG)

358 The migration of paracetamol in SG (Table 3) is associated with a small global  $^{13}\text{C}$  normal isotope  
359 effect of  $-1.1 \pm 0.5\text{‰}$ . This result agrees with previous data obtained during the migration of  
360 vanillin on this stationary phase ( $-0.9 \pm 0.1\text{‰}$ , Table 4) where  $^{13}\text{C}$ -depleted isotopologues are less  
361 retained in the stationary phase (preferentially eluted). The presence of  $^{13}\text{C}$  within paracetamol  
362 molecules seems to result in a higher retention of heavy isotopologues. The PSIA revealed that  
363 this IE is not equitably distributed between the carbon positions with a maximum  $\epsilon$  located on C-  
364 1 ( $-3.3 \pm 1.5\text{‰}$ ). The presence of a strong PSIE on this carbon position can be explained by the

365 presence of hydrogen-bonds between the oxygen of the acetamide function of paracetamol and  
366 acid hydrogens of silanols in SG (see Figure 2). The measurement of a smaller  $\epsilon$  on carbon 6 ( $-2.3$   
367  $\pm 1.6\%$ ) could be due to a secondary PSIE associated with the described interaction. This  
368 deduction is reinforced by the presence of a strong normal  $^{15}\text{N}$  ( $-4.7 \pm 2.5\%$ ) IE during the  
369 migration which could be associated with the interaction of hydrogens from silica gel and the  
370 electron lone pair of the nitrogen atom. Other normal PSIEs located on the aromatic cycle of  
371 paracetamol (carbon positions 4 and 5) may be due to interactions between  $\pi$  electrons and the  
372 stationary phase during the elution. Surprisingly, no significant PSIE is measured on the C-2 of  
373 paracetamol although interactions between this chemical function and silica gel were anticipated.  
374 Intramolecular  $^{13}\text{C}$  isotope data from migration of vanillin in SG are in accordance with these  
375 observations with the presence of a strong normal isotope effect on the carbon bearing the  
376 aldehyde function ( $-3.3 \pm 0.6\%$ ) and a smaller one on the methoxy group ( $-0.9 \pm 0.1\%$ ). The  
377 carbon of the aromatic cycle bearing the alcohol function (C-2) presents an inverse isotope effect  
378 ( $+1.5 \pm 0.4\%$ ) while no significant IE was observed on C-2 of paracetamol. Also, the amplitude of  
379 IEs within the aromatic cycle is higher in the case of vanillin with normal isotope effects with  $\epsilon$   
380 values comprised between  $-1.5 \pm 0.2$  and  $-3,4 \pm 0.2\%$  and an important inverse IE on C-6 ( $+2.4 \pm$   
381  $0.3\%$ ).

382 More generally, the migration of these compounds through a polar stationary phase is associated  
383 with a strong normal  $^{13}\text{C}$  IE inequitably distributed between the carbon positions because of the  
384 presence of polar chemical functions (here acetamide, alkoxy, aldehyde and alcohol) and their  
385 likely contribution to hydrogen bonds set up with the stationary phase.

386 *3.3.2. Cellulose (CE)*

387 Paracetamol migration in CE does not show any significant  $^{13}\text{C}$   $\epsilon_{\text{g}}$  but PSIA revealed the  
388 contribution of both normal and inverse PSIEs on the different carbon positions of the molecule.  
389 In contrast to the SG experiment, the migration of paracetamol in CE is associated with a small  
390 inverse PSIE located on the C-1 ( $+0.4 \pm 0.3\text{‰}$ ). Surprisingly, a normal PSIE is detected on the C-6  
391 ( $\epsilon = -2.4 \pm 0.2\text{‰}$ ) which suggests that the presence of a  $^{13}\text{C}$  on this carbon position may stabilize  
392 the interaction between the oxygen of the acetamide function of paracetamol and those from CE  
393 (Figure 3) resulting in a slower elution of the observed isotopomer. Nevertheless, no significant  
394  $^{15}\text{N}$  isotope fractionation is detected during this experiment. Other carbon positions (3 and 5)  
395 present positive  $\epsilon$  values demonstrating that the presence of  $^{12}\text{C}$  in the aromatic cycle leads to  
396 less stable interactions between paracetamol and CE.

### 397 3.3.3. Activated charcoal (AC)

398 The migration through AC is associated with a small inverse global IE ( $+0.3 \pm 0.0\text{‰}$ ), which is due  
399 to the counteractive contribution of both normal and inverse PSIEs within the molecule. As  
400 explained in the introduction, only weak non-covalent interactions (i.e. van der Waals and  $\pi$ -  
401 stacking) between paracetamol and activated charcoal are expected. A few significant PSIEs are  
402 detected in this case such as a normal PSIE on the C-6 ( $\epsilon = -1.7 \pm 0.6\text{‰}$ ), which could be explained  
403 by the presence of a van der Waals interaction involving this methyl position of paracetamol. A  
404 normal PSIE here suggests that van der Waals interactions can be stabilized by the presence of  
405  $^{13}\text{C}$ , so isotopomers with a  $^{12}\text{C}$  on C-6 will elute faster. Then, carbon positions 2, 3 and 4, located  
406 in the aromatic cycle, present inverse PSIEs of  $+1.0 \pm 0.1\text{‰}$ ,  $+1.6 \pm 0.5\text{‰}$  and  $+0.5 \pm 0.3\text{‰}$   
407 respectively. These observed PSIEs may be due to the  $\pi$ -stacking interactions between  
408 paracetamol and aromatic functions in activated charcoal (Figure 2). According to these data, the



409 presence of  $^{13}\text{C}$  on these carbon positions may stabilize the proposed intermolecular interaction  
410 and induce isotope fractionation during migration. A significant normal  $^{15}\text{N}$  IE is also detected  
411 during the migration of paracetamol in activated charcoal ( $\epsilon = -2.7 \pm 0.9\text{‰}$ ), which could be due  
412 to the presence of van der Waals interaction between activated charcoal and this moiety of  
413 paracetamol.

#### 414 3.3.4. Silica gel C8-reversed phase (RP)

415 No significant  $^{13}\text{C}$  global IE was detected during the migration of paracetamol on RP and only small  
416 intramolecular PSIEs were identified. Previous data obtained from the migration of vanillin on RP  
417 also showed a non-significant global IE (see Table 4). A small inverse PSIE was measured on C-6  
418 of paracetamol ( $\epsilon = +0.3 \pm 0.2\text{‰}$ ) which suggests that van der Waals interactions between this  
419 methyl position and C<sub>8</sub> carbon chains from the stationary phase may be strengthened by the  
420 presence of a  $^{12}\text{C}$  on C-6, so isotopomers with a  $^{13}\text{C}$  on this carbon position are preferentially  
421 eluted. Conversely,  $\epsilon$  of  $-0.3 \pm 0.1\text{‰}$  and  $-0.5 \pm 0.2\text{‰}$  are measured on C-3 and C-4, respectively,  
422 so the presence of  $^{13}\text{C}$  within the aromatic cycle of paracetamol seems to increase the retention  
423 of the considered isotopomers on this stationary phase. A few significant inverse IEs are observed  
424 within vanillin with  $+0.3 \pm 0.1\text{‰}$  on C-5,  $+0.7 \pm 0.5\text{‰}$  on C-3 and  $+1.1 \pm 0.2\text{‰}$  on C-2. This last  
425 isotope effect has a higher amplitude than those observed in paracetamol, but the experimental  
426 conditions used in the present study differed (reversed phase of type C<sub>8</sub> instead of type C<sub>18</sub>,  
427 different eluents, different compounds studied).

428 However, the migration of such polar compounds through nonpolar stationary phases seems to  
429 be associated with only a few small inverse isotope effects.

### 430 3.3.5. Intramolecular $\epsilon$ associated with non-covalent interactions

431 According to data obtained in the present study, the chemical composition of the solid medium  
432 traversed by an organic pollutant has an influence on the associated isotope fractionation. Note  
433 that the same eluent mixture is used during each chromatography experiments so the IEs  
434 potentially created by interactions between eluent and paracetamol are hidden. In this context,  
435 the  $\epsilon$  values measured for each matrix can be used to discuss the link between observed NCIEs  
436 and the chemical structure of the stationary phase. These results suggest that intermolecular  
437 interactions established between the substrate (here paracetamol and vanillin) and the soil  
438 (modeled by various stationary phases in this study) have a direct influence on the selectivity of  
439 isotopomers preferentially migrating. The PSIEs associated with the migration experiments  
440 allowed the identification of the isotopomers that preferentially interact with each of the tested  
441 stationary phases. The presence of small or non-significant global IEs (measured using irm-MS) is  
442 proved to be due to the counteractive contribution of both normal and inverse intramolecular  
443 PSIEs (measured by irm-<sup>13</sup>C NMR) for different carbon positions of the substrate.

444 The key point of the present study is the association of the non-covalent interactions between  
445 the stationary phase and the substrate with the resulting intramolecular PSIEs. As an example,  
446 both SG and CE are polar, so hydrogen-bonds between these stationary phases and paracetamol  
447 or vanillin can be made. The presence of PSIEs on C-1 associated with the migration through these  
448 two materials confirms the presence of hydrogen bonds between acidic hydrogens of the phases  
449 and the oxygen atom of the acetamide function (Table 3). Thus, it can be predicted that when a  
450 polar organic contaminant migrates in a soil containing polar phases, isotope fractionation on the  
451 carbon positions bearing a polar function (alcohol, ketone...) will occur. The presence of

452 intramolecular IEs associated with the formation of hydrogen bonds has already been proven to  
453 be directly correlated in the case of evaporation of VOCs [14]. Conversely, no PSIEs should be  
454 observed on polar functions during the migration in non-polar medium such as AC or RP.

455 The presence of weak interactions, such as van de Waals forces or  $\pi$ -stacking, can also induce  
456 PSIEs but it is much more difficult to discuss any direct implication in the distribution of PSIEs  
457 because they do not involve a specific chemical function of the substrate. The exact chemical  
458 structure of AC is not well defined, but the presence of aromatic cycles is expected in this material.

459 Thus, it is not surprising that significant PSIEs at carbon positions located in the aromatic cycle of  
460 paracetamol and vanillin (Tables 3 and 4) are observed. However, isotope fractionation is also  
461 observed on carbon positions of the aromatic cycle during the migration of paracetamol through  
462 the other stationary phases which may be due to (i) interactions between the  $\pi$  electrons and  
463 acidic hydrogens from SG and CE or (ii) hydrophobic interaction with the C<sub>8</sub> aliphatic chain of the  
464 RP. Similarly, it is hard fully to interpret the significant isotope effect observed on C-6 of  
465 paracetamol and C-8 of vanillin in all experiments (Table 2). This PSIEs could be considered as a  
466 secondary isotope effect due to the presence of hydrogen bonds on the C=O or the O of ether  
467 function for paracetamol and vanillin respectively (for SG and CE) or a direct van der Waals  
468 interaction in the case of the non-polar media (AC and RP). Further research is required to resolve  
469 these problems.

470 Moreover, these data directly demonstrate the value of intramolecular isotope analysis to study  
471 further the origin and fate of organic pollutants. As PSIEs are different depending on the traversed  
472 stationary phase, modeling the isotope fractionation occurring during migration in pure material

473 associated with the chemical analysis of the contaminated soil could help tracing organic  
474 pollutants in the environment.

### 475 3.3.6. Theoretical calculations of the enrichment factors.

476 Theoretical prediction of heavy-atom isotope effects poses numerous problems since they are  
477 usually very small. Reported herein experimental results, obtained for different solid phases,  
478 provided a unique opportunity to evaluate quality of different theoretical models used in  
479 quantum-chemical calculations of isotope effects associated with changes in weak interactions.  
480 The obtained results are collected in Table 5.

481  
482 **Table 5:** Enrichment factors ( $\epsilon$  in ‰) obtained from quantum mechanical calculations for  
483 transition from diethyl ether to aqueous solution (14aq), gas phase, and acetone.

	$\epsilon$ (‰)							
	$C_{\text{bulk}}$	C-1	C-2	C-3	C-4	C-5	C-6	$N_{\text{bulk}}$
<b>14aq</b>	-1.0	-1.6	0.0	-0.9	-0.8	-0.8	-1.9	-4.9
<b>gas</b>	+0.2	+1.2	0.0	+0.5	-0.1	0.0	-0.7	-0.9
<b>acetone</b>	+0.3	+0.8	+0.6	+0.3	+0.4	+0.1	0.0	-0.2

484  
485 The two first entries in Table 5 represent fractionations calculated for the process of going from  
486 diethyl ether solution either to very polar and hydrogen-bonded environment (aq14) or to the  
487 gas phase. As can be seen, except for the value for the C3 position, results obtained using aq14  
488 model are in very good agreement with the experimental results for SG (normal phase silica gel).  
489 We have tried to rationalize this single discrepancy, however, no clear indication of its source has

490 been identified based on the geometrical features and electrostatic properties. The gas phase  
491 model, on the other hand, agrees well with those obtained for the other three solid phases  
492 although not with particular single one. We have, therefore, calculated a putative process of  
493 paracetamol changing phases by going from pure ethyl ether to acetone. These values might  
494 reflect preferential solvation and can be treated as uncertainty on the calculated values.

495 Results collected in Table 3 seem to implicate that the polarity effects dominate over specific  
496 hydrogen bonding interactions since the results obtained for cellulose support are much closer to  
497 those of activated carbon and reverse phase than to those obtained for silica gel. Thus the results  
498 obtained with the apparent solvent model indicate that the presence of the explicit hydrogen  
499 bonding between the paracetamol and solvent molecules of high polarity of the solvent shell  
500 environment results in strong polarization that affects the isotopic fractionation. On the contrary,  
501 when continuum models of solvent are used accounting for these polarization effects is much  
502 weaker leading to lower values of isotopic fractionation.

503

#### 504 **4. Conclusions**

505 The data presented confirm IEs associated with the migration of organic compounds such as  
506 paracetamol, and that the extent of these depend on the matrix through which the considered  
507 chemical is migrating. These results also confirm that when the recovery of a target compound is  
508 not total during isolation by liquid chromatography, its isotope composition may be affected,  
509 especially when followed by intramolecular isotope analysis. Then, the corrections of the  
510 measured isotope data need to consider the chemical composition of both the stationary phase

511 and the isolate molecule in addition to amount of lost compound (see Rayleigh plots). A better  
512 understanding of these “binding isotope effects” should help describing the processes involved  
513 in liquid chromatography and, more generally, in migration experiments. Hence, these results  
514 endorse the need to take the migration into account while studying the isotope composition of  
515 organic contaminants during their remediation. Furthermore, the use of intramolecular isotope  
516 analysis is potentially of considerable benefit for environmental forensic investigations, as they  
517 give indications of the type of matrix through which the pollutant has migrated. The identification  
518 of PSIEs associated with migration experiments should help in understanding the link between  
519 the transport of an organic contaminant and the chemical composition of the soil. This is the main  
520 objective of the present work. Understanding the mechanisms involved is essential to developing  
521 detailed transport models for the prediction of the intramolecular of isotope distribution within  
522 an organic contaminant and its evolution in the environment. As sorption is considered one of  
523 the most promising method to eliminate organic pollutants from water [54,55] the determination  
524 of the PSIEs associated with this process should lead to a better understanding of the mechanisms  
525 involved, hence aid making contaminant monitoring more efficient. Thus, they provide further  
526 insight of value for the characterization of the source(s) and the detection/quantification of  
527 remediation mechanisms. Unfortunately, as NMR has a low sensitivity, large quantities of pure  
528 compound are required to perform PSIA on field samples. However, recent advances in NMR are  
529 making it possible to access the intramolecular  $^{13}\text{C}$  isotope composition using much lower  
530 quantities [56], while other PSIA methods using on-line pyrolysis coupled with irm-MS [22,57] or  
531 high resolution MS [22] are offering opportunities for similar detail to be obtained on much  
532 smaller samples still. Such approaches should make possible experiments in real soil conditions

533 aimed at understanding and modeling the exact link between intermolecular non-covalent  
534 interactions and intramolecular isotope distributions within target molecules. Also, the great  
535 agreement between PSIEs measured by  $^{13}\text{C}$ -NMR and those calculated using theoretical models  
536 demonstrate the great potential of quantum mechanics for predicting the evolution of  
537 intramolecular isotopic composition of organic environmental contaminants. Future  
538 developments of more sensitive intramolecular isotope analysis methods associated with  
539 theoretical calculations should provide excellent tools to trace the origin and fate of organic  
540 compounds detected in environment.

541

#### 542 **Supplementary material**

543 Supporting information is added to this article, see “Supporting\_Information.xlsx”.

544

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554

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