

Determination of sample temperature and temperature stability with ^{129}Xe NMR

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Abstract

The ^{129}Xe chemical shift of xenon dissolved in isotropic liquids is very sensitive to solvent density, which in turn is dependent on the sample temperature. Therefore, the ^{129}Xe chemical shift can be used as the basis of a thermometer for measuring actual sample temperatures in NMR experiments. Good accuracy can be achieved, but the thermometer is particularly useful in monitoring temperature stability. In the present case, carbon tetrachloride (CCl_4), ethylbromide ($\text{C}_2\text{H}_5\text{Br}$), and deuterated chloroform (CDCl_3) were chosen as solvents because of their large thermal expansion coefficient.

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1. Introduction

Modern NMR spectrometers are generally equipped with a built-in variable temperature unit. Temperature is usually determined with a thermocouple positioned just below the sample tube in the probe, meaning that the thermocouple does not measure the actual sample temperature, but the temperature of the surrounding close to the sample. To measure the actual sample temperature, the thermometer has to be placed in the same volume as the sample.

There are a number of physical, temperature-dependent quantities on which a NMR thermometer could be based [1]. The most common, however, is the chemical shift of nuclei, such as ^1H [2–4], ^{13}C [5], ^{19}F [6], ^{31}P [7], and ^{59}Co [8]. In the present case, we introduce a thermometer that is based on the ^{129}Xe chemical shift difference of xenon in the gas phase on one hand and on the other hand in an isotropic solution. The ^{129}Xe nucleus is particularly suitable because its chemical shift range in isotropic solutions is ca. 250 ppm [9]. The ^{129}Xe chemical shift can, in favorable

experimental conditions, be measured to an accuracy of 0.1 Hz. Which, in principle, makes an accuracy of 1–2 mK in temperature feasible. In practice, however, the accuracy is limited by the calibration method used.

Assuming pairwise additivity for xenon shielding perturbations, it appears that ^{129}Xe shielding depends upon the solvent density in isotropic solutions according to [10]

$$\sigma_{\text{Xe}}^{\text{gas}} - \sigma_{\text{Xe}}^{\text{sol}} = \rho^{\text{sol}}(T) \{ \sigma'_0 [1 - \epsilon(T - T_0)] \}, \quad (1)$$

where σ'_0 is the shielding divided by density at $T = T_0$, $\sigma_{\text{Xe}}^{\text{gas}}$ the shielding of xenon gas reference, and ϵ describes the temperature-dependence of shielding. For the chemical shift, we can write, respectively,

$$\Delta\delta_{\text{Xe}}^{\text{sol}} = \delta_{\text{Xe}}^{\text{sol}} - \delta_{\text{Xe}}^{\text{gas}} = \rho^{\text{sol}}(T) \{ \delta'_0 [1 - \epsilon(T - T_0)] \}, \quad (2)$$

where δ'_0 is the chemical shift divided by the density at $T = T_0$. This relation can be utilized in temperature measurements if the temperature-dependence of the solvent density is known. Unfortunately, this is often not the case. Thus, one can apply a linear approximation since, at conventional temperatures, a good approximation for the temperature-dependence of density is

$$\rho^{\text{sol}}(T) = \rho_0^{\text{sol}} [1 - \alpha(T - T_0)], \quad (3)$$

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where ρ_0^{sol} is the solvent density at the reference temperature T_0 and α is the thermal expansion coefficient. Combining Eqs. (1) and (3) leads to

$$\sigma_{\text{Xe}}^{\text{gas}} - \sigma_{\text{Xe}}^{\text{sol}} = \rho_0^{\text{sol}} \sigma'_0 [1 - (\epsilon + \alpha)(T - T_0) + \alpha\epsilon(T - T_0)^2] \approx \sigma_0 [1 - (\alpha + \epsilon)(T - T_0)], \quad (4)$$

where $\sigma_0 = \rho_0^{\text{sol}} \sigma'_0$ is the shielding at the reference temperature T_0 and the second-order term in T has been omitted (α and ϵ are of the order of 10^{-4}). The ^{129}Xe chemical shift relative to the gas reference, $\Delta\delta_{\text{Xe}}^{\text{sol}}$, can, respectively, be represented in the form

$$\Delta\delta_{\text{Xe}}^{\text{sol}} = \delta_0 [1 - (\alpha + \epsilon)(T - T_0)]. \quad (5)$$

2. Experimental

The ^{129}Xe chemical shift of xenon dissolved in a liquid solution was measured relative to the resonance of xenon gas on top of the liquid in the sample tube. Therefore, the test thermometer was constructed so that the liquid level would be so low (approximately in the middle of the receiver coil) that the coil would pick up signals from the two phases simultaneously. In an application construction, xenon and a chosen solvent were introduced into a capillary tube (OD 2.7 mm) which was placed coaxially into a 5 or 10 mm tube, and the actual sample was placed in the annulus of the double tube system [11]. In the present test cases, however, only one of the thermometers (carbon tetrachloride) was prepared into a capillary tube while the others were prepared into a 5 mm tube.

It is preferable to use liquids which possess a large thermal expansion coefficient and a wide liquid range. Furthermore, it is advantageous if the solvent does not show resonances that could significantly disturb the spectrum of the molecules under investigation. Therefore, carbon tetrachloride and ethylbromide were chosen as solvents. ^{129}Xe isotopically enriched (70%) xenon gas was used in the $\text{C}_2\text{H}_5\text{Br}$ solution (equilibrium pressure ca. 2 atm) and in the CCl_4 solution (equilibrium pressure ca. 6 atm).

Another option would be to prepare the thermometer sample without a gas–liquid boundary. This would make the use of the thermometer a lot easier in practice because of the easier adjustment of B_0 field homogeneity. In that case there is no resonance of free xenon gas, but one can choose a deuterated solvent so that the use of a lock is possible. When the lock is applied, it is possible to just read the chemical shift value from the spectrum. CDCl_3 was chosen as a solvent and natural abundance xenon gas (equilibrium pressure ca. 5 atm) was used in this case.

The NMR measurements were performed on the Bruker Avance DRX500 and DPX200 spectrometers, equipped with BVT2000 and BVT3200 variable temperature units, respectively. The thermometer was calibrated by measuring the ^1H chemical shifts in standard samples: (a) 4% methanol in methanol- D_4 and (b) 80% ethylene glycol in DMSO. The measurements proceeded so that the spectra of the

calibration sample and the thermometer were taken consecutively and repeated several times at each temperature. The experimental parameters for the xenon thermometer calibration experiments were the following: a pulse length of 4–13 μs , a relaxation delay of 5–60 s, and a number of scans of 1–100. The temperature was changed in steps of 1–10 K and it was allowed to stabilize for at least 60 min after each change.

3. Results and discussion

3.1. Dependence of the ^{129}Xe chemical shift on solvent density

The temperature-dependence of liquid densities is commonly represented in the form [12]

$$\rho(T) = \rho_0 + 10^{-3}\alpha'(T - T_0) + 10^{-6}\beta'(T - T_0)^2 + \dots \quad (6)$$

where ρ_0 is the density at the reference temperature T_0 and the coefficients α' , β' , etc. are derived from the experimental data. An equation in the form of (6) allows the calculation of solvent density at any temperature. The parameters ρ_0 , α' , and β' for carbon tetrachloride and ethyl bromide are shown in Table 1. The fit of Eq. (2) to the experimental data led to the following equations:

(a) xenon in carbon tetrachloride

$$\Delta\delta_{\text{Xe}}^{\text{exp}}(T) = \rho^{\text{sol}}(T)(138.75 \text{ ppm g}^{-1} \text{ cm}^3)[1 - 5.92 \times 10^{-4} \text{ K}^{-1}(T - T_0)] \quad (7)$$

the standard deviation of the fit being 0.03 ppm, and

(b) xenon in ethylbromide

$$\Delta\delta_{\text{Xe}}^{\text{exp}}(T) = \rho^{\text{sol}}(T)(132.04 \text{ ppm g}^{-1} \text{ cm}^3)[1 - 4.59 \times 10^{-4} \text{ K}^{-1}(T - T_0)] \quad (8)$$

the standard deviation of the fit being 0.12 ppm.

3.2. Dependence of the ^{129}Xe chemical shift on sample temperature

As stated above, generally the temperature-dependence of the solvent density is not known and then equations like (7) and (8) cannot be applied. Thus, the temperature-dependence of density can be approximated by applying the linear function shown in Eq. (3). The least-squares fits of the experimental densities to this equation led to α values of $12.491 \times 10^{-4} \text{ K}^{-1}$ and $13.718 \times 10^{-4} \text{ K}^{-1}$, and ρ_0 values of 1.6376 g cm^{-3} and 1.5023 g cm^{-3} for carbon tetrachloride and ethylbromide, respectively. In both cases, the errors of

Table 1

The parameters of the density function, Eq. (6), for carbon tetrachloride and ethyl bromide [12]

Compound	ρ_0 (g cm^{-3})	α' ($\text{g cm}^{-3} \text{ K}^{-1}$)	β' ($\text{g cm}^{-3} \text{ K}^{-2}$)
CCl_4	1.63266	-1.9119	-0.690
$\text{C}_2\text{H}_5\text{Br}$	1.50138	-2.0644	0.2673

Reference temperature $T_0 = 273 \text{ K}$ in both cases.

densities are smaller than the contribution of the second-order term in Eq. (6). On the other hand, least-squares fits of the experimental ^{129}Xe chemical shifts to Eq. (5) result in the $(\alpha + \epsilon)$ values of $17.42 \times 10^{-4} \text{ K}^{-1}$ for carbon tetrachloride and $18.55 \times 10^{-4} \text{ K}^{-1}$ for ethylbromide. Consequently, the parameter ϵ gets the values $4.928 \times 10^{-4} \text{ K}^{-1}$ and $4.830 \times 10^{-4} \text{ K}^{-1}$ in CCl_4 and $\text{C}_2\text{H}_5\text{Br}$, respectively. These ϵ values are ca. 30% of the respective $(\alpha + \epsilon)$ values indicating that the solvent density clearly has a larger contribution to the temperature dependence of the ^{129}Xe chemical shift than the xenon-solvent pair correlation function [10].

The relations between the ^{129}Xe chemical shift and temperature are obtained by least-squares fits of the experimental chemical shifts and calibrated temperatures to equations of the form $\Delta\delta_{\text{Xe}}^{\text{exp}}(T) = A_1T + B_1$ and $T = A_2\Delta\delta_{\text{Xe}}^{\text{exp}}(T) + B_2$, which can be derived from Eq. (5). The fits result in the equations shown below:

(a) xenon in carbon tetrachloride

$$\Delta\delta_{\text{Xe}}^{\text{exp}}(T) = -0.3937T + 333.95, \quad (9)$$

$$T = -2.5397\Delta\delta_{\text{Xe}}^{\text{exp}} + 848.14 \quad (10)$$

and

(b) xenon in ethylbromide

$$\Delta\delta_{\text{Xe}}^{\text{exp}} = -0.3670T + 299.34, \quad (11)$$

$$T = -2.7049\Delta\delta_{\text{Xe}}^{\text{exp}} + 809.71. \quad (12)$$

In Eqs. (9)–(12), the chemical shift is given in ppm and temperature in K. The achievable accuracy for measuring temperatures with the thermometer described here depends primarily on the calibration method. Namely, the $\Delta\delta_{\text{Xe}}^{\text{exp}}$ chemical shift can, in favorable circumstances, be measured with an accuracy of better than 0.002 ppm within intermediate temperatures, corresponding to an accuracy of 5–6 mK in temperature. With the used calibration samples the estimated accuracy was ca. 0.07 K for the CCl_4 based meter and 0.7 K for the $\text{C}_2\text{H}_5\text{Br}$ based meter. These figures were derived from the standard deviation of the least-squares fits. The worse accuracy in the latter case is attributed to the distorted lineshapes detected at extreme temperatures and the wider temperature range, within which the linear approximation is not as valid as within a narrower range. Furthermore, calibration was carried out using both methanol and ethylene glycol NMR thermometers and their readings did not match. For example, at 300 K the two readings differed by 0.88 K. This obviously leads to an increase in the error bars.

Relations between the ^{129}Xe chemical shift and temperature were obtained for a sample without the gas–liquid boundary as well:

(c) xenon in deuterated chloroform

$$\Delta\delta_{\text{Xe}}^{\text{exp}} = -0.3861T + 323.51, \quad (13)$$

$$T = -2.5898\Delta\delta_{\text{Xe}}^{\text{exp}} + 837.87. \quad (14)$$

The results are shown graphically in Fig. 1. In Eqs. (13) and (14), the accuracy of the fit is not as good as in other two cases because of the severe broadening of the linewidth at temperatures far from room temperature. Reasons for the broadening are discussed in the following section.

3.3. Stabilization of the sample temperature

From Eqs. (10) and (12) it can be seen that the gradients, $dT/d(\Delta\delta_{\text{Xe}})$ are -2.5397 and $-2.7049 \text{ K ppm}^{-1}$ for the Xe/CCl_4 and $\text{Xe}/\text{C}_2\text{H}_5\text{Br}$ thermometers, respectively. At the external magnetic field of 11.74 T, the corresponding values in Hz are -18.4 and -19.4 mK Hz^{-1} . In carefully performed experiments, $\Delta\delta_{\text{Xe}}^{\text{exp}}$ can be measured with an accuracy of ca. 0.002 ppm, meaning that the achievable temperature resolution is ca. 5–6 mK. In the case of the CDCl_3 sample the linewidth in the spectrum was less than 0.1 Hz at its best. Consequently, temperature could be determined with the accuracy of 1–2 mK. This property makes these thermometers particularly applicable for controlling temperature stability.

Fig. 2 displays a good example of the sensitivity of the xenon thermometer. The Xe/CDCl_3 thermometer was used to monitor temperature for 30 min. The heater was turned off and flowing gas was neither cooled nor heated. The FWHM of the observed peaks was less than 0.3 Hz and the S/N ratio 85. During the experiment the peak position changed 0.012 ppm which corresponds to a change of 0.03 K in temperature. Due to the sharp lineshape, even much smaller changes (0.002–0.005 K) in temperature could possibly be observed.

When the heater is turned on the conditions change rapidly. Because of the extreme sensitivity of the xenon shielding, even the slightest temperature gradient over the sample causes broadening of the linewidth. The temperature gradient may also cause thermal convection [13]. Thermal convection causes an even more severe broadening of the linewidth, because “cold” molecules from the upper part of the sample volume flow to the coil region and measured ^{129}Xe resonance frequency is different due

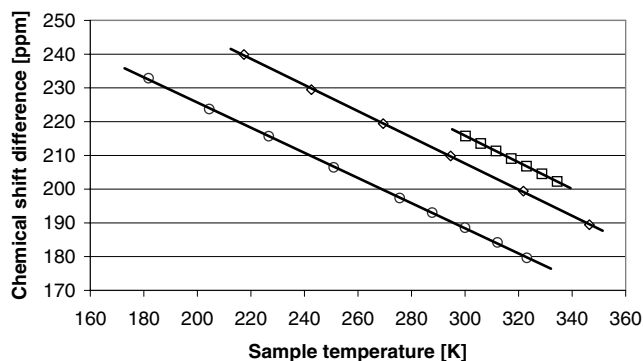


Fig. 1. Temperature dependence of chemical shift of xenon dissolved in CCl_4 (squares), in $\text{C}_2\text{H}_5\text{Br}$ (circles), and in CDCl_3 (diamonds). Solid lines represent Eqs. (9), (11), and (13).

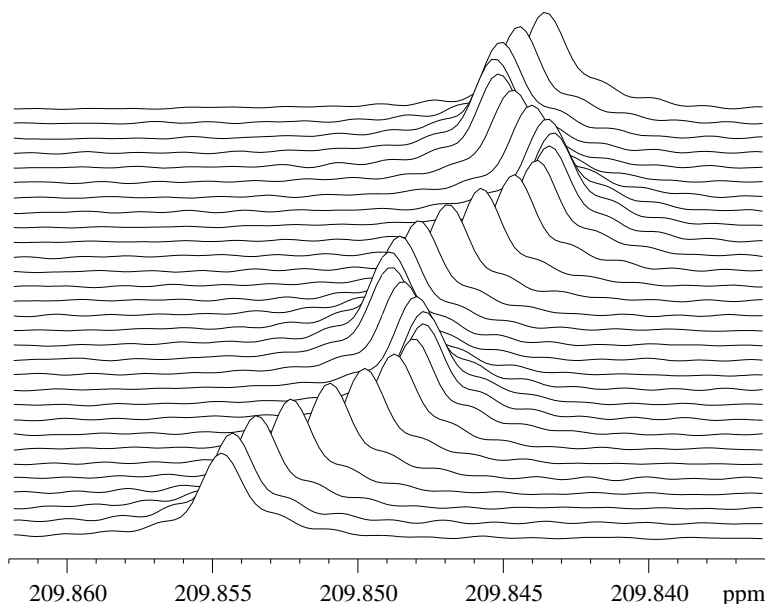


Fig. 2. Single scan ^{129}Xe NMR spectra of xenon gas dissolved in CDCl_3 measured at 1 min intervals. During a 30 min experiment the temperature has changed only 0.03 K, but that is easily observed in the spectrum.

to the difference in density. It has been proven that sample rotation eliminates convection [14]. The spinning of the sample substantially narrowed linewidths. However, sample rotation does not remove temperature gradients. For example, a gradient of 0.2 K cm^{-1} over the receiver coil region broadens the linewidth by 10 Hz. Unfortunately, it seems that these gradients appear every time the heater is turned on. It has been suggested that increasing the gas flow rate would reduce the temperature gradients, but not even that seemed to help in this case [15]. When using a thermometer with the gas–liquid boundary, the broadening of linewidth is less visible since the height of the solvent inside the receiver coil is smaller.

In another experiment, temperature stabilization time was studied. Measurements were carried out using the Xe/CCl_4 thermometer. The temperature was increased or decreased by several degrees (up to 30 K) and then switched back to 300 K. The ^{129}Xe NMR experiments were started when the thermometer of the temperature control unit indicated that the set temperature was reached. The spectra were collected in steps of a few minutes. Only after about 2 h did it appear that the temperature did not vary more than 0.05 K. The results are shown in Fig. 3.

In principle, any liquid could be used as a solvent in a ^{129}Xe NMR thermometer. In other words, it would be possible to equip most liquid NMR samples with an internal NMR thermometer by inserting xenon gas in the sample. This requires calibration measurements for every substance used, but makes it possible to follow even the slightest changes in sample temperature. For example, the possible heating effect of high power irradiation could be easily observed.

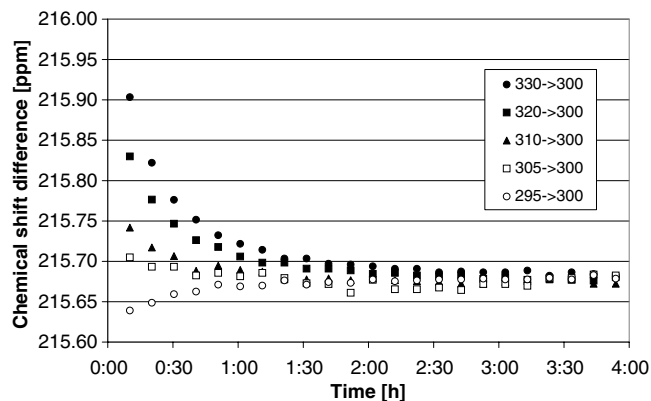


Fig. 3. ^{129}Xe chemical shift difference, $\Delta\delta_{\text{Xe}}^{\text{exp}}$, as a function of time in the CCl_4 solution. The clock was started at the time when the set temperature, 300 K in each case, was reached according to the VT unit. The sample was heated to 330 K (black circles), 320 K (black squares), 310 K (black triangles), and 305 K (open squares) or cooled to 295 K (open circles).

4. Conclusions

The ^{129}Xe chemical shift is very sensitive to sample temperature. For example, in the solvents CCl_4 , CDCl_3 , and $\text{C}_2\text{H}_5\text{Br}$ used in this study the sensitivity is almost 0.4 ppm K^{-1} , that is ca. 55 Hz K^{-1} at the magnetic field of 11.74 T. When utilizing isotopically enriched xenon gas, chemical shift can be measured with high accuracy. Consequently, temperature is also obtained with high accuracy. The achievable accuracy of thermometer readings, however, critically depends upon the means chosen for thermometer calibration. Experiments described in this paper show that the presented thermometers are particularly suitable for monitoring temperature stability. If the main purpose is to observe temperature stability, it is sufficient to

detect only the ^{129}Xe resonance signal of xenon in a liquid. A thermometer setup without a gas–liquid boundary is very accurate and easy to use. Changes of 1–5 mK in temperature are observable in optimal experimental conditions.

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