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Determination of the Dipolar Interaction of ^{23}Na in Solution by Triple-Quantum Relaxation Time Measurements

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The measurement of the dipolar interaction of ^{23}Na with hydrogen nuclei in glycerol solution is reported. The method, applied previously to ^{7}Li (U. Eliav and G. Navon, *J. Magn. Reson. A* **123, 32 (1996)), is based on the measurement of the triple-quantum relaxation time of ^{23}Na. Several models of motion are discussed. The analysis of the results yielded 1.9 MHz and 12.5 kHz for the quadrupolar and the ^{23}Na–^{1}H dipolar interaction, respectively. It is shown that under the conditions of long correlation times the triple-quantum relaxation time can be sensitive to dipolar interactions smaller than the quadrupolar interaction by as much as a factor of 5000. This indicates the possibility of measuring interatomic distances for nuclei with sizable quadrupolar moments.**

Recently it has been suggested that it is possible to assess the dipolar interaction strength of quadrupolar nuclei using the relaxation times of multiple-quantum coherences (*1*). It was shown theoretically that coherences associated with the $I \leftrightarrow -I$ transitions are the most suitable for this purpose (*1*). Experimentally this theoretical notion was demonstrated by measuring the dipolar interaction between protons and ^{7}Li ($I = 3/2$) using the triple-quantum relaxation time. In these experiments the ratio between the quadrupolar and the dipolar interactions is typically 12 so that while the T_1 and fast component of T_2 are dominated by the quadrupolar interaction the relaxation times of the $m \leftrightarrow -m$ ($m = 1/2, \ldots, I$) transitions are dominated by the dipolar interaction. It was interesting to see whether for large ratios between quadrupolar and dipolar interactions is it still possible to measure the dipolar interaction. For example, for ^{23}Na the ratio is of the order of 500 (*1*). In the present work we show that even for such a nucleus the dipolar interaction can be assessed for solutions where the molecular motion is sufficiently slow.

The experiments were carried out on 200 mM NaCl dissolved in glycerol at temperatures of −29 and −18°C. The effect of the dipolar interaction was studied by comparing the triple-quantum-filtered (TQF) and single-quantum NMR experiments. The effect of the dipolar interaction was further verified by examining the effect of replacing the solvent protons by deuterons on the above experiments. Specifically, d_8-glycerol was used as solvent. To increase the amount of information all experiments were carried out with magnetic field strengths of 8.47 and 11.74 T. The instruments used were Bruker AMX 360 and ARX 500 operating at sodium resonance frequencies of 95.3 and 132.4 MHz, respectively.

At a temperature of −29°C the satellite transitions ($\pm 3/2 \leftrightarrow \pm 1/2$) are very broad (>100 kHz) and excitation in our experiment was selective. This, however, does not exclude the formation of triple-quantum coherence (*2*). A three-pulse sequence

$$90^\circ - \tau - P_1 - t_1 - P_1(\text{acq.}, t_2) \tag{1}$$

with suitable phase cycling has been used to select the following pathway: 0, −1, ±3, −1, thus obtaining a TQF signal. The selection of the above pathway was checked by measuring the dependence of the TQF spectral intensity on the time interval t_1 as a function of the offset of the carrier frequency from resonance (*3–5*). It was found to oscillate with a frequency which was three times that of the offset frequency, as expected of the TQF spectrum.

The dynamic frequency shift of the triple-quantum coherence (*3, 5*) was measured by setting the carrier frequency on the single-quantum resonance and measuring the change of the intensity of the TQF spectrum as a function of t_1. The result was fitted to the following expression, obtaining the dynamic shift (DS) and triple-quantum relaxation time (T_{TQ}):

$$S(t_1) = \cos(\text{DS}\ t_1 + \varphi)e^{-t_1/T_{\text{TQ}}}. \tag{2}$$

A spin echo pulse sequence with a suitable phase cycling (*6, 7*) was used to measure the relaxation time of the sodium center band transition ($T_{2\text{s}}$). The values of the two relaxation times ($T_{2\text{s}}$ and T_{TQ}) and the dynamic shift (DS) at two magnetic fields, for two solvents, and at two temperatures are given in Tables 1 and 2. As can be seen from the tables the relaxation times either increase or do not change upon increasing the magnetic field. Thus chemical shift anisotropy or chemical exchange can be ruled out as an important relaxation mechanism. The fact that the DS is independent of the

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TABLE 1

Experimental and Theoretical Values of the Relaxation Times and Dynamic Shifts of the $|m\rangle \leftrightarrow |-m\rangle$ (m = 1/2, 3/2) Transitions of ^{23}Na at a Temperature of −29°C[a]

B_0:	8.46 T		11.74 T	
Solvent:	Glycerol	d_8-Glycerol	Glycerol	d_8-Glycerol
T_{2s} (ms)	0.81 (0.77, 0.81)	1.10 (1.11, 1.19)	1.10 (1.12, 1.11)	2.00 (2.04, 1.82)
T_{TQ} (ms)	0.31 (0.25, 0.26)	0.85 (0.75, 0.82)	0.25 (0.28, 0.28)	1.00 (1.07, 1.03)
DS/2π (Hz)	5170 (5200, 5210)	5230 (5230, 5210)	3780 (3760, 3780)	3840 (3780, 3800)

[a] The values in the parentheses are theoretical values obtained by fitting the expressions given in Eqs. [3] to the experimental results using two theoretical models for the motion, one that assumes different correlation times for quadrupolar and dipolar interactions (the first value in parentheses) and a second one that assumes a Cole–Davidson distribution of correlation times (the second value in parentheses). The experimental errors are ±8% for T_{2s}, T_{TQ}, and DS.

solvent deuteration suggests that it is mostly determined by quadrupolar interaction. Furthermore, at the two temperatures it has the same value (Tables 1 and 2). Thus we conclude that the spins move very slowly, fulfilling the condition $\omega_0\tau_C \gg 1$, where ω_0 is the Zeeman frequency and τ_C is the reorientation correlation time. With this condition in mind and making the approximation of isotropic motion the relaxation parameters are given by the expressions (*1, 5, 8–10*)

$$\frac{1}{T_{2s}} = R_{2s}^{Q} + R_{2s}^{Q}(\text{secular}) + R_{2s}^{D} \qquad [3a]$$

$$\frac{1}{T_{TQ}} = R_{TQ}^{Q} + R_{TQ}^{Q}(\text{secular}) + R_{TQ}^{D}$$

$$R_{TQ}^{Q} = R_{2s}^{Q} = \frac{\chi^2}{16\omega_0^2\tau_C} \qquad [3b]$$

$$R_{TQ}^{Q}(\text{secular}) = \frac{21}{149}\,R_{2s}^{Q}(\text{secular}) = \frac{3\chi^4}{16{,}000\omega_0^2}\,\tau_C \qquad [3c]$$

$$R_{TQ}^{D} = 9R_{2s}^{D} = \frac{12}{5}\,I(I+1)D^2\tau_C \qquad [3d]$$

$$\text{DS} = \frac{3\chi^2}{20\omega_0}, \qquad [3e]$$

where χ and D are the quadrupolar and dipolar interactions, respectively, and they are related to microscopic parameters by the expressions

$$\chi = \frac{e^2qQ}{\hbar}, \quad D = \gamma_S\gamma_I\hbar\sum\frac{1}{r_i^3}, \qquad [4]$$

where q is the electric field gradient at the sodium nucleus and Q is its quadrupole moment, and γ_S and γ_I are the gyromagnetic ratios of the sodium nucleus and heteronucleus, respectively. In the current study the heteronuclei are ^{1}H ($I = 1/2$) or ^{2}H ($I = 1$). The distances between the sodium nucleus and heteronuclei are given by r_i.

An attempt to fit Eqs. [3] to the experimental data yielded an unreasonably large value for the dipolar interaction ($D/2\pi > 64$ kHz) and an exceptionally short correlation time ($\tau_C \sim 22$ ns at a temperature of −29°C) and hence this model was abandoned. A more meaningful model was obtained on the basis of the assumption that the dipolar and quadrupolar interactions are affected by different motions. Thus in Eqs. [3b] and [3c] we substituted τ_C by τ_C^Q and in Eq. [3d] τ_C was replaced by τ_C^{dip}. For this model the expressions in Eqs. [3] were fitted to the experimental results by using χ, τ_C^Q, and $D^2\tau_C^{\text{dip}}$ as free parameters. Since the viscos-

TABLE 2

Experimental and Theoretical Values of the Relaxation Times and Dynamic Shifts of the $|m\rangle \leftrightarrow |-m\rangle$ (m = 1/2, 3/2) Transitions of ^{23}Na at a Temperature of −18°C[a]

B_0:	8.46 T		11.74 T	
Solvent:	Glycerol	d_8-Glycerol	Glycerol	d_8-Glycerol
T_{2s} (ms)	0.59 (0.55, 0.60)	0.65 (0.59, 0.60)	0.93 (1.00, 0.92)	1.0 (1.1, 1.02)
T_{TQ} (ms)	0.42 (0.41, 0.44)	0.53 (0.53, 0.59)	0.60 (0.60, 0.60)	0.92 (0.92, 0.93)
DS (Hz)	5100 (5100, 5140)	4800 (5000, 4830)	3700 (3650, 3690)	3700 (3600, 3630)

[a] See comments in footnote to Table 1.

TABLE 3
The Microscopic Parameters Used to Fit Eq. [3] to the Experimental Data[a]

Temperature:	$t = -18°C$		$t = -29°C$	
Solvent:	Glycerol	d_8-Glycerol	Glycerol	d_8-Glycerol
$\chi/2\pi$ (MHz)	1.8	1.8	1.8	1.8
τ_C^Q (ns)	13	13	26	26
$D^2\tau_C^{\text{dip}}$ (s^{-1})	430	≈ 10	1800	60

[a] The experimental errors are ±4% for χ and ±8% for τ_C^Q and $D^2\tau_C^{\text{dip}}$.

ity of glycerol and d_8-glycerol may not be the same (*11*) the fitting for the two solvents was done separately. The results of the fitting to the experimental data at temperatures of −29 and −18°C are given in Tables 1 and 2, respectively. The fitted parameters χ, τ_C, and $D^2\tau^{\text{dip}}$ are given in Table 3. The contributions of the various terms in Eq. [3] to the relaxation rates are summarized in Table 4. It is apparent from Table 4 that the most significant contribution to the relaxation rates stems from the nonsecular quadrupolar and dipolar terms. Moreover, at a magnetic field of 11.74 T and a temperature of −29°C the contribution of the dipolar interaction between sodium and protons to the relaxation time (T_{2s}) of the single-quantum transition $1/2 \leftrightarrow -1/2$ is comparable to that of the quadrupolar interaction and it makes a much larger contribution to the triple-quantum coherence relaxation time (T_{TQ}). This result is fully in accordance with theory prediction that even very small dipolar interaction can affect the TQ relaxation. For instance, taking $D/2\pi = 400$ Hz, $\chi/2\pi = 2$ MHz ($\chi/D = 5000$) and $\omega_0 2\pi = 150$ MHz one obtains from Eq. [3] that the effect of dipolar and quadrupolar interactions on the TQ relaxation is comparable for $\tau_c = 1.5\ \mu s$. As expected of the dipolar interaction, deuteration of the solvent caused a reduction of its effect on the relaxation times but nevertheless its contribution to triple-quantum relaxation is still comparable to that of the quadrupolar interaction. Thus we conclude that for the magnetic fields typical of the current study the modulation of the quadrupolar and the dipolar interactions is the most significant mechanism for the relaxation of the sodium nuclei. This conclusion is different from previously suggested relaxation mechanisms that attributed significant importance either to the secular terms of the quadrupolar interaction or to the modulation of chemical shift anisotropy (*12*).

In order to examine the dynamics of sodium in glycerol we discuss the modulation of the dipolar and quadrupolar interactions separately. We start our discussion with relaxation caused by the quadrupolar interaction. The values of χ and τ_C^Q were found to be the same for both solvents, indicating the possibility of a small dependence on the viscosity. This notion is further supported by the temperature dependence of τ_C^Q which decreases by only a factor of 2 upon raising the temperature from −29 to −18°C while for the viscosity one has $\eta(-29°C)/\eta(-18°C) = 5.4 \pm 0.5$ in glycerol.

On the other hand the relaxation caused by the modulation of the dipolar interaction is more sensitive to the solvent viscosity as is seen from examining the effect of the temperature on τ_C^{dip} in glycerol. It decreases by 4.2 ± 0.4 as the temperature is increased from −29 to −18°C, comparable with a decrease by a factor of 5.4 ± 0.5 of the viscosity in

TABLE 4
The Contributions of the Various Terms Given in Eq. [3] to the Relaxation Rates at a Temperature of −29°C[a]

B_0:	8.46 T		11.74 T	
Solvent:	Glycerol	d_8-Glycerol	Glycerol	d_8-Glycerol
R_{2s}^Q, R_{TQ}^Q [b]	890, 870	830, 710	460, 550	430, 460
R_{2s}^Q (secular)	1.4, 21	1.4, 70	0.7, 11	0.7, 35
R_{2s}^D	350, 340	56, 55	350, 340	56, 55
R_{TQ}^Q (secular)	0.2, 3.0	0.2, 10	0.1, 1.5	0.1, 5
R_{TQ}^D	3160, 3050	510, 500	3160, 3050	510, 500

[a] The pairs of values given for each parameter are the theoretical values obtained by fitting the expressions given in Eq. [3] to the experimental results using two theoretical models for the motion, one that assumes a single reorientation time (the first value) and a second model that assumes a Cole–Davidson distribution of correlation times (the second value). All relaxation rates are given in s^{-1}.

[b] The values of R_{2s}^Q and R_{TQ}^Q are identical (Eq. [3]).

glycerol. The above difference in the dependence of τ_C^{dip} and τ_C^{Q} on the viscosity indicates that they are correlation times of different motions. This notion is further supported if one estimates the absolute values of τ_C^{dip}. As the average internuclear distance between the sodium ion and 32 hydrogen atoms in its solvation shell is expected to be significantly larger than 2.2 Å, one obtains $D/2\pi \ll 17$ kHz. Thus, on the basis of the value of $D^2\tau_C^{dip}$ (Table 3) τ_C^{dip} (glycerol) $\gg 220$ ns, a value which is significantly larger than the value of τ_C^{Q} (26 ns, Table 3). There may be a number of possible ways to account for the difference between the correlation times τ_C^{Q} and τ_C^{dip}. One way is to envisage two distinct types of motions that modulate the dipolar and quadrupolar interactions. Other explanations are anisotropic motion or isotropic motion but with a distribution of correlation times. For all these possibilities the shorter correlation time is expected to determine the spectral densities of the quadrupolar interaction and the longer correlation time is expected to determine those of the dipolar interaction. Two models of anisotropic motion were fitted to the current study data. One model is the one presented by Woessner (*13*) and encompasses two motions: a whole isotropic motion of the molecule and an internal anisotropic one. This model has been recently applied to studies of ^{7}Li (*1*). The second anisotropic motion model is a modification (*14*) of Woessner's rigid body motion model (*15*). Both models fitted the experimental data well. The first anisotropic model (*1, 13*) yielded $D/2\pi = 17$ kHz and $\tau_M = 240$ ns for the whole molecule motion correlation time and $\tau_1 = 56$ ns for the correlation time of the internal anisotropic motion. The second anisotropic motion model (*14*) yielded 22 kHz for the dipolar interaction and three correlation times $\tau_1 = 1500$ ns, $\tau_2 = 53$ ns, and $\tau_3 = 2200$ ns. However, it is difficult to envisage a model which will account for this wide range of correlation times. Moreover the fitted values of the dipolar interaction of the sodium with the protons require an averaged internuclear distance shorter than 2.2 Å, a very unlikely value. Thus we examine the possibility that both quadrupolar and dipolar interactions are modulated by the same isotropic motion with a continuous distribution of correlation times. As an example of such a distribution we adopt the model introduced by Cole and Davidson (*16*) which proved to be useful in dielectric relaxation studies (*16, 17*) as well as in NMR studies of protons (*18, 19*) and ^{13}C (*19*). The Cole–Davidson distribution is (*16, 20*)

$$g(\tau_C) = \begin{cases} \dfrac{1}{\tau_C}\left(\dfrac{\tau_C}{\tau_0 - \tau_C}\right)^{\beta}, & 0 < \tau_C \le \tau_0 \\[2ex] 0, & \tau_C > \tau_0, \end{cases} \qquad [5]$$

where τ_0 is the cutoff correlation time and β $(0 < \beta \le 1)$ is the breadth of the distribution. The real (*18*), $J(\omega_0)$, and imaginary, $Q(\omega_0)$, parts of the complex spectral density are obtained from the expression

$$J(\omega_0) + iQ(\omega_0) = \int_0^{\tau_0} \frac{\tau_C g(\tau_C)}{1 + i\omega_0\tau_C}\, d\tau_C \qquad [6]$$

and their explicit expressions are given by

$$J(\omega) = \frac{\sin[\beta tg^{-1}(\omega_0\tau_0)]}{\omega_0[1 + (\omega_0\tau_0)^2]^{\beta/2}}$$

$$Q(\omega) = \frac{1}{\omega_0}\left\{1 - \frac{\cos[\beta tg^{-1}(\omega_0\tau_0)]}{[1 + (\omega_0\tau_0)^2]^{\beta/2}}\right\}. \qquad [7]$$

The dynamic shift is related to $Q(\omega_0)$ by

$$\mathrm{DS} = \frac{\chi^2}{10}(2Q(\omega_0) - Q(2\omega_0)). \qquad [8]$$

It can be seen from Eq. [7] that under extreme narrowing conditions $(\omega_0\tau_0 \ll 1)$ $J(\omega_0) = \beta\tau_0$; i.e., all the complex spectral densities are equal and are proportional to a single correlation time (the imaginary parts vanish).

Under slow motion conditions the expressions for the relaxation times (Eq. [3]) can be used, provided that the correlation time in Eq. [3b] takes the form

$$\tau_C = \tau_0(\omega_0\tau_0)^{\beta-1} \qquad [9]$$

while in Eqs. [3c] and [3d] the correlation times are substituted by

$$\tau_C = \beta\tau_0. \qquad [10]$$

The main difference between the present approach which assumes a distribution of correlation times and the one with two correlation times (τ_C^{Q} and τ_C^{dip}) is that in the present approach under slow motion conditions the correlation time of the motion that modulates the secular terms of the quadrupolar interaction (Eq. [9]) depends on ω_0. The microscopic parameters obtained by fitting Eqs. [3], [9], and [10] to the experimental results at temperatures of −18 and −29°C are listed in Table 5. During the fitting procedure it has been assumed that the strengths of the quadrupolar and dipolar interactions do not change with temperature while the breadth (β) and the cutoff correlation time (τ_0) of the Cole–Davidson distribution may change. One may note that the ratio of the D values obtained for the two solvents at −29°C is very close to $\gamma(^1\mathrm{H})/\gamma(^2\mathrm{H})$ as one can expect on the basis of Eq. [4] if the internuclear distances are the same for the two solvents. The values of the relaxation times and dynamic shifts calculated on the basis of the parameters given in Table 5 are shown in Tables 1 and 2 in parentheses. The

TABLE 5

The Microscopic Parameters That Were Obtained by Fitting the Expressions of the Relaxation Rates and Dynamic Shift Which Were Based on the Cole–Davidson Distribution to the Experimental Data[a]

Temperature:	$t = -18$°C		$t = -29$°C	
Solvent:	Glycerol	d_8-Glycerol	Glycerol	d_8-Glycerol
$\chi/2\pi$ (kHz)	1900	1900[b]	1900	1900
$D/2\pi$ (kHz)	12.5	—[c]	12.5	1.9
τ_0 (ns)	160	—[c]	690	2000
β	0.40	—[c]	0.40	0.34

[a] The experimental errors are ±4% for χ, D, and β and ±8% for τ_0. All relaxation rates are given in s^{-1}.

[b] χ is determined by the dynamic shift (see Eq. [8]).

[c] Due to the small effect of the dipolar interaction in d_8-glycerol at a temperature of −18°C, the experimental errors of D, β, and τ_0 are very large and thus their values are not given.

contributions of the various terms to the relaxation rates and dynamic shift are summarized in Table 4 along with the results of the isotropic motion model that incorporated two correlation times (see previous paragraphs). Comparison of the two models show that for both of them the most significant contributions to the relaxation rates stem from the dipolar interaction and the nonsecular term of the quadrupolar interaction while the secular term of the quadrupolar interaction is insignificant.

As can be seen from Tables 1 and 2 the fit of the Cole–Davidson model is as good as that of the two correlation times model. However, it seems more plausible, since instead of a very short discrete value for τ_C^Q that does not have a clear physical meaning, the value of τ_C^Q that emerges from the Cole–Davidson model represents the lower end of a continuous distribution. Furthermore, the values of τ_0 and β found in the current work for a temperature of −18°C ($\tau_0 = 160$ ns and $\beta = 0.4$, see Table 5) are close to values obtained for glycerol by other types of measurements. Interpolation of the values of τ_0 and β obtained by analyzing the T_1 of protons and deuterons at temperatures of −17 and −23°C (*18*) gave $\tau_0 = 125$ ns and $\beta = 0.53$. Similarly, interpolation of dielectric relaxation data (*17*) for −18°C gave $\tau_0 = 190$ ns and $\beta = 0.6$. The agreement between the values obtained by the different experiments seems to be reasonable in view of the different effect that the distribution of correlation times has on each of these techniques. Moreover, slight contamination of the glycerol solutions with water affects significantly the viscosity and may contribute to the differences between the results obtained by the various methods (*17*). The value of 12.5 kHz obtained for the dipolar interaction on the basis of the Cole–Davidson distribution leads to a lower limit of 2.5 Å for the average sodium–proton distance, a plausible limit for a solution of sodium dissolved in glycerol.

The present work leads to the conclusion that for sufficiently slow motion the dipolar interaction is equal to or even more effective than the quadrupolar interaction in relaxing the $m \leftrightarrow -m$ ($m = 1/2, \ldots, I$) transitions of ^{23}Na nuclei in spite of their sizable quadrupole moment. This makes it possible to estimate internuclear distances for quadrupolar nuclei.

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