Accelerated Relaxation of Sensitive Nuclei for Enhancement of Signal-to-Noise with Time

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A pulse sequence is proposed that accelerates the relaxation of sensitive nuclei through inverse polarization transfer from insensitive nuclei that have been subject to NOE during their detection: the sequence is designed to replace normal intersequence relaxation delays. Typically, for the observation of $\{^1H\}$–^{13}C, the ^{13}C relaxes during data acquisition and is enhanced by NOE from decoupled ^1H's. After data acquisition the ^{13}C polarization can be transferred to ^1H in order to step-jump accelerate the relaxation of ^1H and hence provide ^1H polarization more rapidly for transfer to ^{13}C during the next repetition of polarization-transfer sequences. It is suggested that the sequence (SNARE) can advantageously replace the relaxation delays in many common sequences. The benefits of so doing are illustrated using PENDANT and DEPT for ^{13}C investigations. Conditions for the implementation of SNARE are proposed, and it is demonstrated that there is a range of spectral-acquisition parameters of practical interest for which the method can be beneficial. Experimental time savings in achieving a chosen S/N typically exceed 30%.   © 1997 Academic Press

INTRODUCTION

One disadvantage of many NMR investigations is their time-consuming nature that stems from lengthy relaxation delays. Few methods exist for the reduction of natural spin–lattice relaxation delays. The most popular depends on the addition of relaxation agents (*1*), but this may often be chemically undesirable. A more complex way is via the ultrasonic irradiation (*2*) of analytical samples, but the methodology of this approach remains complex. A different approach to effectively reducing spin–lattice relaxation times (T_1) is now proposed. The basis of this is to modify the relaxation of the sensitive nucleus (I) by employing polarization transfer from S to I through the manipulation of spin–spin coupling interactions between the heteronuclei. This paper focuses on the new method, applicable to the latter type of spin system, that results in sensitive-nucleus accelerated relaxation for enhancement (SNARE) of the spectral signal-to-noise ratio of the insensitive nucleus during a given

experimental time. The method benefits from both polarization-transfer and nuclear Overhauser enhancement effects.

THEORETICAL

SNARE depends on polarization transfer in the opposite sense [in a manner similar to that employed in the original version of inverse spectroscopy (*3*)] to that commonly employed (*4–6*), viz., from the insensitive to the sensitive nuclei. Necessarily, this imposes basic requirements on the spin system studied. These include the normal condition that the T_1 of I is shorter than that of S, and additionally that the relaxation time of S is reasonably short, for example, on the order of three times that of I. These conditions are often encountered in those air-saturated samples, containing *J*-coupled ^{13}C–^1H spin systems, that are at the heart of many routine NMR investigations. SNARE, which may in principle replace the relaxation delay that precedes any conventional pulse sequences, also relies on the frequently used condition that the I nuclei are decoupled from S during acquisition. Consequently, to benefit from the NOE the gyromagnetic ratios of the sensitive and insensitive nuclei must be of the same sign. If they are not, even gated decoupling will not suppress the negative NOE on the S that relaxes during acquisition: work on this problem is in progress.

During the course of acquiring the spectrum of S while I is decoupled following a conventional pulse sequence, the situation is that while there should ideally be no I_z magnetization, S_z develops with nuclear Overhauser enhancement (NOE, defined here as $\eta = \gamma^I/2\gamma^S$) of the S-spin polarization toward the maximum value of the enhanced magnetization which is $(\gamma^I/2\gamma^S) + 1$ times the normal S magnetization (M_0^S). The enhanced transient S magnetization can be transferred to the I spin immediately after switching off the decoupler signal to I, and so accelerate the recovery of the I spin toward its equilibrium value. The situation may be summarized simply for a spin-$\frac{1}{2}$ only I–S system as in Table 1, which is intended purely to illustrate the principle at the heart of SNARE for a system at equilibrium without refer-

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TABLE 1
Idealized Energy-Level Populations in a CH Spin System, under Various Conditions ($x \to 0$ and $0 < y \leqslant 3$)

	(H–C) population			
	$\beta\beta$	$\beta\alpha$	$\alpha\beta$	$\alpha\alpha$
1. Equilibrium	$-4-1$	$-4+1$	$+4-1$	$+4+1$
2. ^{1}H decoupled	< ⋯⋯⋯⋯ 0−2 ⋯⋯⋯⋯>			
		< ⋯⋯⋯⋯ 0+2 ⋯⋯⋯⋯>		
3. After decoupling	$-x-y$	$-x+y$	$+x-y$	$+x+y$
4. Antiphase ^{13}C	$-x-y$	$-x+y$	$+x+y$	$+x-y$

ence to the effects of other magnetization manipulation or relaxation.

Table 1 specifically represents the principles implicit in SNARE as applied to a ^{1}H–^{13}C spin system: the populations of the four energy levels are idealized by assuming that the ^{1}H polarization is four times that of ^{13}C, with each of the relevant spin states having equally increased or decreased populations relative to the zero magnetic field condition. Step 1 represents the normal equilibrium situation. In step 2 it is assumed that decoupling is completely effective, but that Overhauser enhancement of the ^{13}C has not commenced, so that there is zero net population difference between the ^{1}H levels, but the population between the ^{13}C levels follows a Boltzmann distribution. Step 3 represents the situation immediately after ^{13}C acquisition in an appropriate investigative sequence, with the ^{1}H decoupling terminated; to accommodate switching times on stopping the decoupling process a small population, x, of the ^{1}H levels is assumed to have occurred. During ^{13}C acquisition it is assumed that the ^{13}C populations have reached $|y| \leqslant 3$. Stage 3 reveals z-phase magnetizations for ^{13}C, and in the limit when $x = 0$, no ^{1}H z magnetization. However, if one of the ^{13}C magnetization components is inverted (step 4), enhanced antiphase ^{1}H z magnetizations [$(-2x - 2y)$ and $(-2x + 2y)$] are immediately regenerated. The latter can be refocused using standard procedures and returned rapidly to z phase so that the ^{1}H relaxation is step-jump accelerated along its normal pathway, thus facilitating a reduction in the relaxation delay necessary to obtain a chosen S/N that might be required under normal conditions. It must be emphasized that the advantage of using SNARE with a constant relaxation delay is realized only when $x < y$ and is at a maximum when $x = 0$ and y corresponds to the maximum NOE on S.

Assuming single-exponential relaxation decays of the I (and S) nuclei, the normal relaxation of I during the relaxation delay, D_r, is described by

$$M_z^I = M_0^I[1 - \exp(-D_r/T_1^I)] \qquad [1]$$

when starting from zero magnetization. However, if the S magnetization recovers to

$$M_z^S = M_0^S(\eta + 1)[1 - \exp(-t_{ac}/T_1^S)] \qquad [2]$$

under NOE conditions during the acquisition time t_{ac}, and its polarization is then inverse-transferred to I, the magnetization of the latter reaches

$$M_{zs}^I = M_0^I[1 - \exp(-D_r/T_1^I)]$$
$$+ \exp(-D_r/T_1^I)M_0^S(\eta + 1)$$
$$\times [1 - \exp(-t_{ac}/T_1^S)]\gamma_I/\gamma_S \qquad [3]$$

using the same D_r after SNARE. In general, the percentage increase (E) in I magnetization that may be obtained using SNARE, relative to that achieved by normal relaxation of I, is, if $M_0^I = M_0^S(\gamma_I/\gamma_S)^2$,

$$E = 100[1 - \exp(-t_{ac}/T_1^S)]$$
$$\times (\eta + 1)\gamma^S/[\exp(D_r/T_1^I) - 1]\gamma^I. \qquad [4]$$

In the above equations, M_0^S and M_0^I are the normal Boltzmann magnetizations of S and I, respectively; M_z^S and M_z^I are the corresponding relaxation-dependent normal magnetizations and M_{zs}^I is that reached in SNARE, all after the delay D_r; and T_1^S (NOE dependent) and T_1^I are the relaxation times of S and I, respectively.

If, for an air-saturated {^{1}H}–^{13}C system, typical values of $t_{ac} = D_r = 1$ s, $T_1^S = 10$ s, $T_1^I = 5$ s, $\eta = 2$, and $\gamma^I = 4\gamma^S$ are inserted into Eq. [4], it can be seen that the ^{1}H z magnetization should be readily increased by 32%. This extra ^{1}H magnetization that can be gained during D_r is now available for subsequent polarization transfer to the ^{13}C. Alternatively, a given ^{13}C S/N can be achieved by reducing D_r and maintaining the number of scans, or by leaving D_r unchanged and reducing the number of scans by 43%.

The consideration of an IS system alone, as illustrated through Table 1, is inadequate for deriving a general experimental procedure for SNARE. The reason for this is that, for S multiplets having more than two components, it is possible to invert level populations by producing antiphase z magnetizations in several ways. Attention is drawn, therefore, to Table 2 which relates to $I_{n(=1-3)}$S spin systems, e.g., CH, CH$_2$, and CH$_3$. For convenience it is assumed that the I spins are completely saturated and that the S spins have recovered along their NOE relaxation pathways to (for convenience) a situation corresponding to their normal Boltzmann-level populations which are represented by unit increase or decrease relative to the zero-field condition (the values ± 1 can of course be replaced by $\pm y$ as in Table 1 to confer some correspondence with experimental reality if required). For the time being it will be assumed that some magnetization evolution and pulse-manipulation technique such as that implicit in the classical INEPT (4) or more

TABLE 2

**Ideal Boltzmann- and Perturbed-Level Populations, and S-Multiplet Intensities Achieved
by Various Transition Manipulations for S{$I_{n=1-3}$} Nuclear Spin Systems**

	Populations		S transitions inverted	I (S = α/β) doublet intensities	
	Boltzmann	Perturbed			
S{I}				S = β	S = α
1. $\beta\{\beta\}$	−1	+1	(1−2)	(1−3) = +2	(2−4) = −2
2. $\alpha\{\beta\}$	+1	−1			
3. $\beta\{\alpha\}$	−1	−1			
4. $\alpha\{\alpha\}$	+1	+1		Σ = +2	Σ = −2
S{I$_2$}					
1. $\beta\{\beta\beta\}$	−1	+1	(1−2)	2(1−3) = +4	2(2−4) = −4
2. $\alpha\{\beta\beta\}$	+1	−1		2(3−5) = 0	2(4−6) = 0
3. $\beta\{\beta\alpha\}$; $\beta\{\alpha\beta\}$	−1 −1	−1 −1			
4. $\alpha\{\beta\alpha\}$; $\alpha\{\alpha\beta\}$	+1 +1	+1 +1			
5. $\beta\{\alpha\alpha\}$	−1	−1			
6. $\alpha\{\alpha\alpha\}$	+1	+1		Σ = +4	Σ = −4
S{I$_3$}					
1. $\beta\{\beta\beta\beta\}$	−1	+1	(1−2)	3(1−3) = +6	3(2−4) = −6
2. $\alpha\{\beta\beta\beta\}$	+1	−1	and	3(5−7) = +6	3(4−6) = +6
3. $\beta\{\beta\beta\alpha\}$; $\beta\{\beta\alpha\beta\}$; $\beta\{\alpha\beta\beta\}$	−1 −1 −1	−1 −1 −1	(5−6)	3(3−5) = −6	3(6−8) = −6
4. $\alpha\{\beta\beta\alpha\}$; $\alpha\{\beta\alpha\beta\}$; $\alpha\{\alpha\beta\beta\}$	+1 +1 +1	+1 +1 +1			
5. $\beta\{\beta\alpha\alpha\}$; $\beta\{\alpha\beta\alpha\}$; $\beta\{\alpha\alpha\beta\}$	−1 −1 −1	+1 +1 +1			
6. $\alpha\{\beta\alpha\alpha\}$; $\alpha\{\alpha\beta\alpha\}$; $\alpha\{\alpha\alpha\beta\}$	+1 +1 +1	−1 −1 −1			
7. $\beta\{\alpha\alpha\alpha\}$	−1	−1			
8. $\alpha\{\alpha\alpha\alpha\}$	+1	+1		Σ = +6	Σ = −6

recent PENDANT (*6*) sequences can be used to produce the required antiphase *z* magnetizations and transfer. The S(I) example serves to illustrate that, if antiphase S_z components are generated (see Fig. 1), the corresponding polarizations can be transferred to the I spin as soon as the saturating decoupler field applied to it is switched off. Turning to the S(I$_2$) system, two possibilities for the production of antiphase magnetizations arise. Referring to Fig. 1, either the two outer components may be inverted relative to the central transition, or alternatively, just one of the outer components may be inverted relative to the other two. It emerges that the first possibility would result in the proposed procedure producing no net observable I magnetization. However, the second possibility (illustrated in Fig. 1) results in the desired situation depicted in Table 2. In the case of S(I$_3$), either pair of adjacent multiplet components may be inverted relative to the other pair or the alternate pairs may be inverted. Either approach leads to the same net effect on the I magnetization. The situation corresponding to the first possibility shown in Fig. 1 is detailed in Table 2.

Reference to Table 2 reveals that the implicit principles can result in antiphase components of equal magnitude for each spin system, and if these can be refocused and ultimately returned to the *z* axis, the magnitudes of the total I polarizations produced by the accelerated relaxation should ideally be, without NOE, 1, $\frac{1}{2}$, and $\frac{1}{3}$, in units of S polarization, for SI, SI$_2$, and SI$_3$, respectively.

In order to decide how to approximate experimentally the processes idealized in Table 2, attention must be focused necessarily on the S(I$_2$) system because of the two possibilities (with different outcomes) that were mentioned above for the manipulation of the S spin. Assuming that the NOE-enhanced S magnetization components that are achieved by relaxation during acquisition are nutated by 90° from the $z(B_0)$ axis to the y(detection) axis and subsequently allowed to evolve, it is only possible to achieve the required antiphase situation by employing $\pm y$ 90° pulses. Fortunately, the same pulses will result in the desired process for both the S(I) and S(I$_3$) systems. The next point that must be addressed is whether to use an inverse process based on a true polarization-transfer sequence such as INEPT (*4*) or to use a polarization-exchange sequence such as PENDANT (*6*). In principle, it becomes a fine decision, because, after the accelerated relaxation of the I spins, the condition of the S spins is not too important as it is the subsequent I relaxation that governs the recovery of the S(I$_n$) systems toward equilibrium. However, the advantages of PENDANT are twofold. First, because this sequence is completely symmetrical, and therefore involves true polarization exchange, it is possible to return any residual S magnetization components in phase
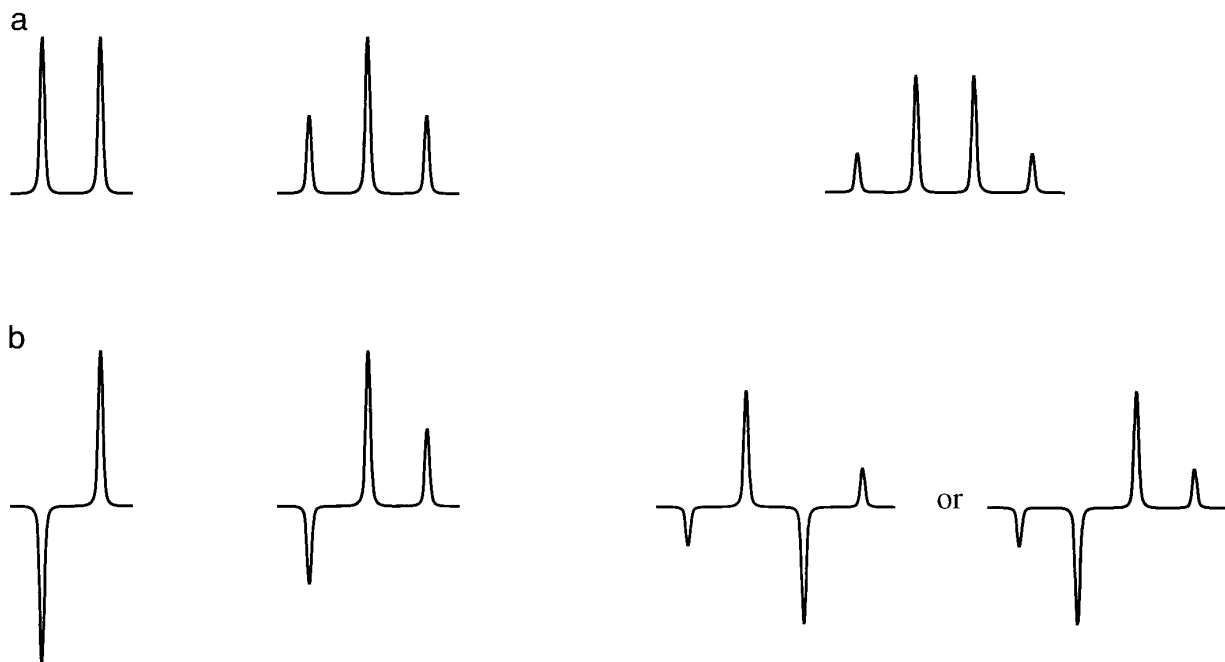
FIG. 1. Schematic representation of the ideal S-multiplet manipulation from the normal (a) to that required (b) for the accelerated relaxation of I magnetization.

along the z axis. Second, PENDANT enables the manipulation of isolated S spins synchronously with those in IS systems. In other words, despite the necessary manipulation of the IS systems, it proves possible to leave essentially unaffected the isolated S-spin z magnetization that has developed during the acquisition period.

The benefits of SNARE can be achieved by replacing the normal intersequence delay, which precedes conventional pulse sequences, by the symmetric PENDANT-type sequence

$$
\begin{array}{llllll}
I & 90^{\circ}_{+x} & D1 & 90^{\circ}_{+y} & D2 & 90^{\circ}_{-x} & D_r \\
S & 90^{\circ}_{+x} & & 90^{\circ}_{+y} & & 90^{\circ}_{-x} &
\end{array}
$$

This sequence is phased to enable each repetitive cycle to start with multiplet components having the frequency labels appropriate to the equilibrium Boltzmann situation: for general use shift refocusing should be introduced by inserting simultaneous 180°_{+x} pulses on S and I at the midpoint of each delay. Although the first 90°_{+x} pulse to I might appear unnecessary because the initial value of I_z should be zero, it is included to accommodate any small value that might exist as a consequence of delays during switching periods. In product-operator formalism (7), the polarization-magne-

tization-exchange pathway from S_y for $n = 1$ to 3 is, neglecting the angular dependencies of J evolution,

$$
S_y \xrightarrow{D1} -\sum_{i=1}^{i=n} 2S_x I_{iz} \xrightarrow{\pi/2(+y,\text{H\&C})}
$$

$$
+ \sum_{i=1}^{i=n} 2I_{ix}S_z \xrightarrow{D2}
$$

$$
+ \sum_{i=1}^{i=n} I_{iy} \xrightarrow{\pi/2(-x,\text{H\&C})} + \sum_{i=1}^{i=n} I_{iz}.
$$

A particular advantage of this sequence is that isolated S nuclei, such as quaternary ^{13}C, are returned to z phase so that they relax normally. The delays $D1$ and $D2$ must be chosen to be compatible with the $S(I_n)$ system under study. For example, if only CH groups were studied, both delays would ideally be $1/2J$. However, as systems under study often contain a range of groups, such as CH, CH_2, and CH_3, $D1$ must be chosen to optimize ^{13}C component evolution and $D2$ the ^{1}H evolution.

The situations depicted in Table 2 assume ideal conditions for each spin system. In reality, the SNARE manipulation of all of the systems simultaneously means that all cannot be exactly on-resonance nor can $D1$ be chosen to match each of the actual J values. Even if the $S(I_3)$ system
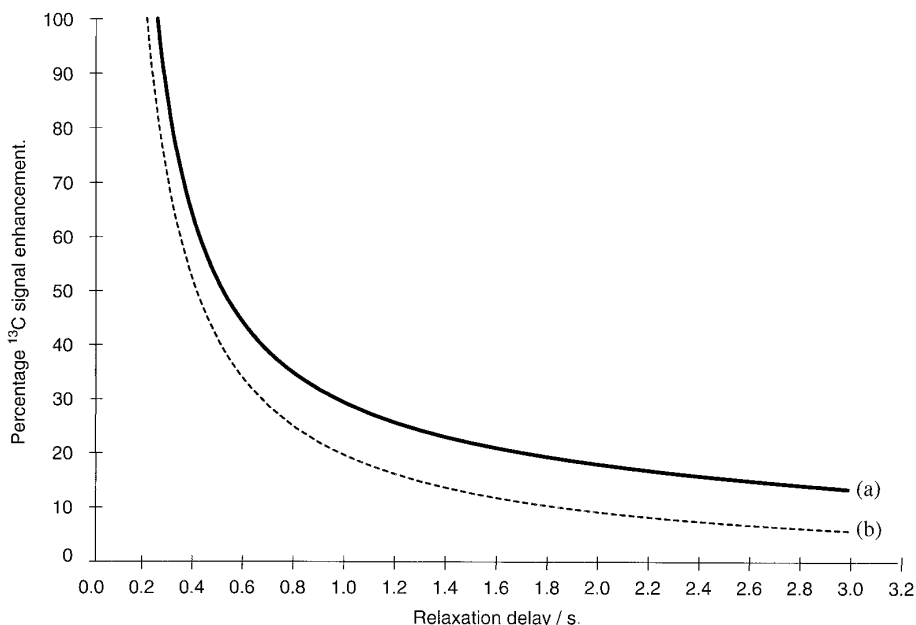
FIG. 2. Experimental (a) and predicted (b) percentage enhancements of the ^{13}C spectra of $CHCl_3$ obtained by using S-PENDANT relative to PENDANT with an acquisition time of 1.9 s with a range of relaxation delays.

is treated ideally, values for $D1$ may be chosen so that either adjacent or alternate multiplet components can be inverted. While both operations will have similar effects on the repolarization of I_3, reality dictates that some com-

promise value of $D1$ will have to be chosen to optimize the inverse polarization of I in each of the spin systems. In general terms, realistic choices of compromise values for $D1$ will favor the inverse polarization of I in $S(I)$ and
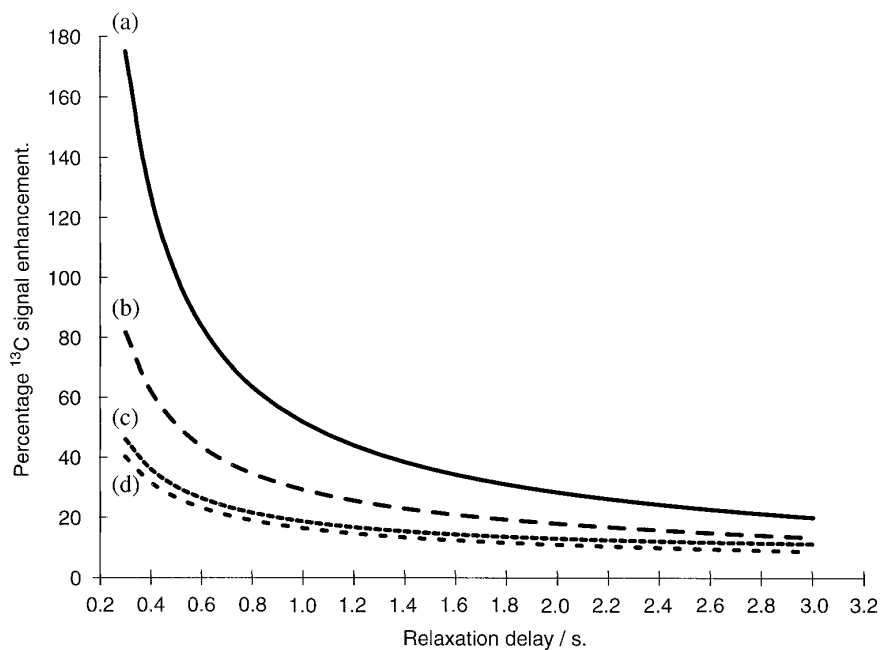
FIG. 3. Experimental percentage enhancements of the ^{13}C spectra of $CHCl_3$ obtained by using S-PENDANT relative to PENDANT with several acquisition times (a, 1.9 s; b, 0.95 s; c, 0.534 s; d, 0.119 s) and a range of relaxation delays.
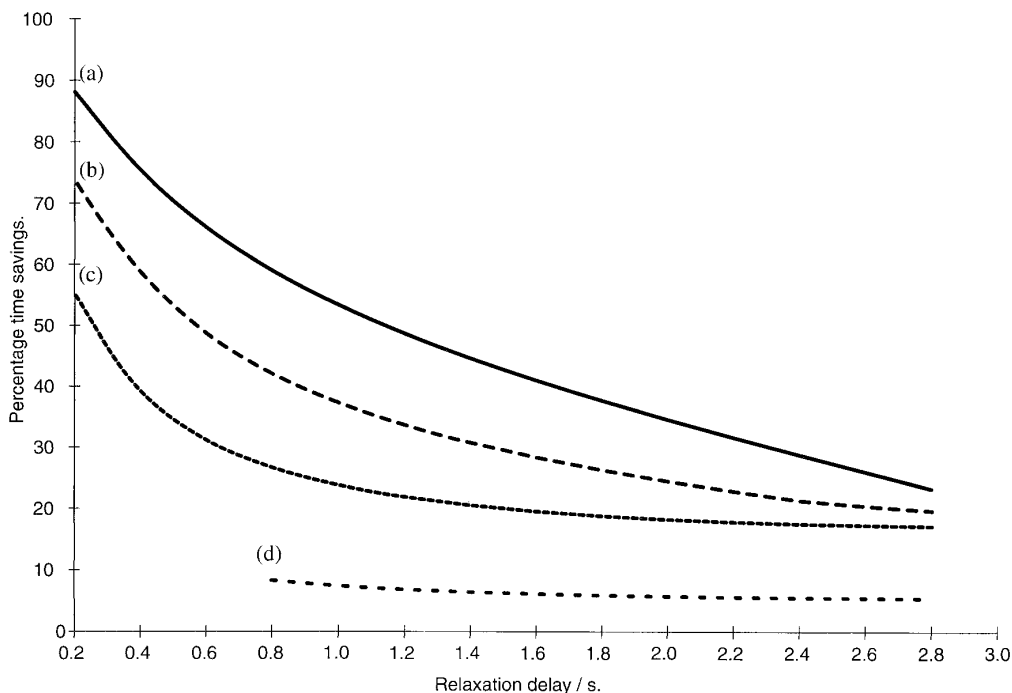
FIG. 4. Experimental percentage time savings achieved when obtaining a chosen ^{13}C spectral S/N for CHCl$_3$ through the use of S-PENDANT relative to PENDANT with several acquisition times (as for Fig. 3) and a range of relaxation delays.

S(I$_2$) at the expense of that in S(I$_3$). For a sample that contains species having I–S coupling constants in the ranges 140–180, 120–140, and 120–140 Hz for S(I), S(I$_2$), and S(I$_3$) systems, respectively (typical for ^{13}C–^{1}H), computer simulations indicate that a suitable compromise value for $D1$ in {^{1}H}–^{13}C studies is $0.325/J$ with $\langle J \rangle$ set at 145 Hz. Neglecting NOE effects, these conditions result in 0.863, 0.48, and 0.293 unit of carbon polarization being inverse-transferred, which compare quite favorably with the maximum inverse repolarizations of ^{1}H by 1, $\frac{1}{2}$, and $\frac{1}{3}$ unit of the ^{13}C polarization (see Table 2) for the CH, CH$_2$, and CH$_3$ groups, respectively.

Turning to the choice of $D2$, if the S doublets in each of the spin systems have similar values of J, it is appropriate to set $D2 = 1/2J$. Consistent with common practice for ^{13}C–{^{1}H} systems, $\langle J \rangle$ could be set at 145 Hz.

EXPERIMENTAL

The various principles implicit in SNARE were examined initially through investigations of suitable air-saturated samples by comparing the ^{13}C spectra obtained using PENDANT with those obtained with the relaxation delay in PENDANT replaced by SNARE (S-PENDANT). Apart from the PENDANT and DEPT(135°) sequences relevant to Fig. 5 discussed later, the sequences were not phase cycled: there is, of course, little point in phase cycling SNARE as any I$_{xy}$

components that exist during the actual relaxation part of the cycle will normally be destroyed by T_2 relaxation. It is interesting to note that the relevant coherence pathways in S-PENDANT (S → I → S) are opposite to those (I → S → I) proposed by Bodenhausen and Ruben (8) in the original double transfer of polarization.

A Bruker AC 300 multinuclear pulse FT NMR spectrometer was used for the investigations. Comparative data were obtained using conditions of constant phase and amplitude. All spectra were obtained from samples thermostated at 298 K in order to minimize variations in S/N due to temperature fluctuations. Where appropriate, ^{1}H and ^{13}C T_1 data were obtained by the well-known inversion-recovery method and NOEs were measured under the conditions specified by Harris and Newman (9).

RESULTS AND DISCUSSION

For the initial investigations an air-saturated sample of CHCl$_3$, containing a small quantity of CDCl$_3$ for field-frequency locking purposes, was used. For this sample, the ^{1}H (satellite) and ^{13}C T_1 values were measured as 8.45 and 23.4 s, respectively, and the {^{1}H}–^{13}C NOE was found to be 1.411. With ^{1}H and ^{13}C at exact resonance and using $D1 = D2 = 1/2J$ with the exact value of the short-range ^{1}H–^{13}C coupling constant (209 Hz), spectra were obtained using both S-PENDANT and PENDANT.

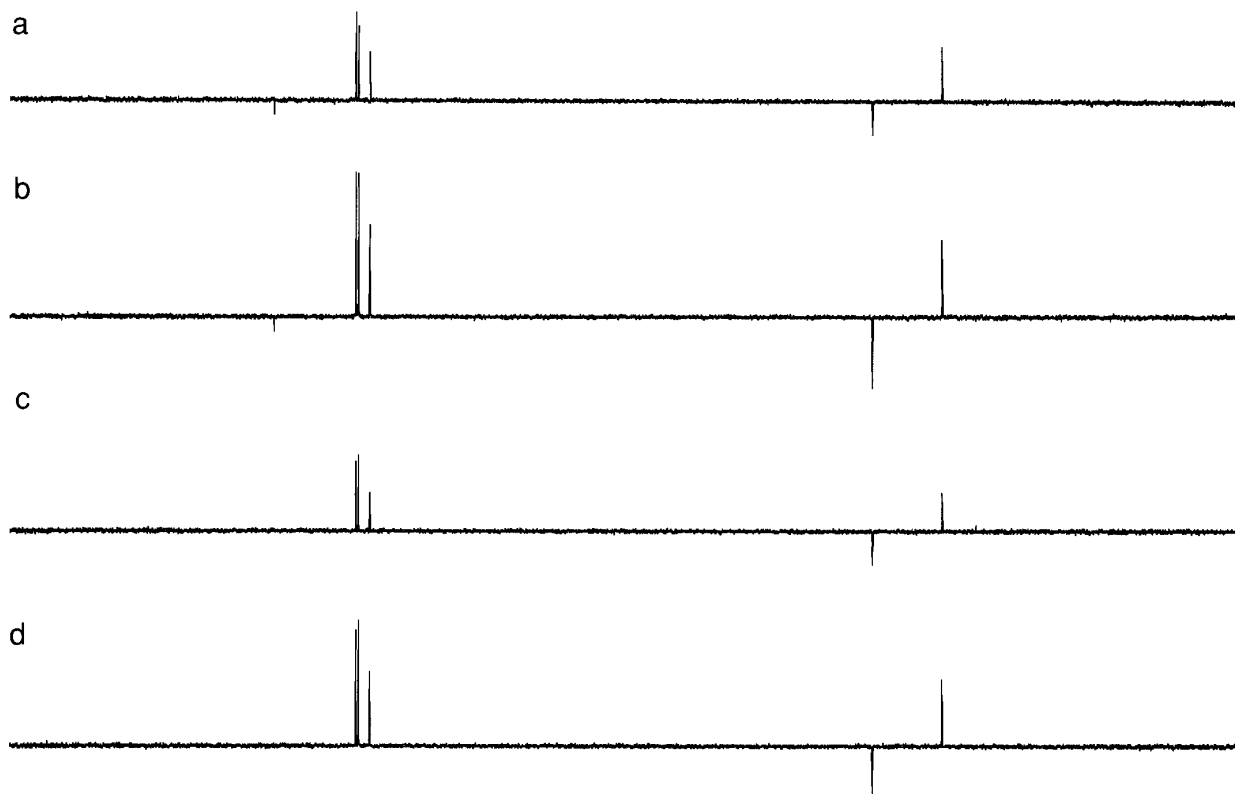**FIG. 5.** ^{13}C spectra of ethylbenzene obtained by using (a) PENDANT, (b) SNARE–PENDANT, (c) DEPT (135°), and (d) SNARE–DEPT (135°): $\langle J \rangle = 135$ Hz in PENDANT and DEPT (135°) and $\langle J \rangle = 160$ Hz in SNARE.

Figure 2 presents typical experimental and predicted percentage increases in signal intensities as a function of total relaxation delay, obtained by using S-PENDANT, relative to those obtained by using PENDANT: these particular data were obtained from 64K data-point spectra with an acquisition time of 1.9 s. As in general, the experimental data in Fig. 2 reveal that significant signal enhancements can be obtained by replacing a conventional relaxation delay by SNARE. It can be seen clearly that, as D_r increases, the enhancements become smaller due to the step-jump repolarization of ^{1}H having a smaller effect on the extent to which the ^{1}H polarization approaches the Boltzmann condition at very long values of D_r.

It must be emphasized that the actual signal enhancement obtained by using SNARE is always significantly greater than that predicted by Eq. [4]. This is attributed to the fact that the predictive equation is based on the assumption that the relaxation of both the ^{13}C during acquisition and the ^{1}H after switching off the decoupler is truly single exponential. While this is reasonable in the former case it is unlikely to be true in the latter case, for which multiexponential behavior will work to the advantage of SNARE.

Figure 3 shows the percentage increases in signal intensity obtained by using SNARE with several acquisition times

and a range of values for the total relaxation delay. It can be seen that the benefits of using SNARE are greater the longer the acquisition time used. Of possibly greater importance to routine use of NMR spectroscopy is the percentage saving in spectrometer time that SNARE enables in the achievement of a particular signal intensity obtained by a standard pulse sequence with a conventional relaxation delay. Figure 4 shows such data, and it can be seen that the time saving can be highly significant, particularly for the longer acquisition times and shorter total relaxation delays. In order to emphasize the conclusions drawn above, attention is drawn to data obtained under the commonly used routine conditions based on 32K spectra obtained with an acquisition time of 0.95 s and a relaxation delay of 1.5 s. These reveal that, in a fixed investigative time, S-PENDANT, relative to PENDANT, permits a percentage increase in signal intensity of 22, or the achievement of a fixed S/N with a 30% time saving: the corresponding values for an acquisition time of 1.9 s are approximately 36 and 41%.

Turning now to the practicalities of using SNARE for studies of molecules containing S, S(I), S(I$_2$), and S(I$_3$) nuclear systems, it is evident from the earlier discussion that the inverse repolarization of I will be largest for the S(I) group. Naturally, it will prove beneficial to equalize the repo-

larization advantages across the range of $S(I)$, $S(I_2)$, and $S(I_3)$ systems. Simulation indicates that this is possible to some extent by using $D1 = 1/4J$ and $D2 = 1/2J$. However, the advantages to the $S(I_2)$ and $S(I_3)$ systems are not greatly improved and an alternative method of compromise is necessary. For this SNARE is set to maximize the advantage to $S(I)$ and PENDANT is set to favor the enhancement of $S(I_2)$ and $S(I_3)$. In $\{^1H\} - {}^{13}C$ investigations, the latter condition can be achieved by reducing $\langle J \rangle$ from the recommended value of 145 Hz to 135 Hz (a further reduction is inadvisable because this will reduce the range of actual J values that can be embraced to ensure reliable spectral editing). With $\langle J \rangle$ set at 135 Hz in PENDANT it is found that the value of $\langle J \rangle$ in $D1$ ($0.325/J$) and $D2$ ($1/2J$) in SNARE is best set at 160 Hz. The benefits of using these parameters are revealed by the spectra of ethyl benzene that are presented in Fig. 5.

The ${}^{13}C$ spectrum of ethylbenzene (Fig. 5a) obtained using PENDANT with $\langle J \rangle = 135$ Hz is compared with the corresponding S-PENDANT spectrum (Fig. 5b), obtained as recommended above and using $D_r = 0.5$ s and $t_{ac} = 1.84$ s. It can be seen that while SNARE has little effect on the intensity of the quaternary ${}^{13}C$ resonance, it effectively doubles the S/N of the other resonances. When D_r is increased, the benefits of using SNARE are reduced as expected. Nevertheless, it was found that the S/N obtained using PENDANT with $D_r = 2$ s can be equalled approximately when S-PENDANT with $D_r = 1.5$ s is used; the time saving will evidently prove beneficial in routine ${}^{13}C$ NMR investigations.

The versatility of SNARE is illustrated through the comparison of the DEPT (135°) and S-DEPT(135°) $\{^1H\} - {}^{13}C$ spectra of ethyl benzene in Figs. 5c and 5d. A detailed comparison of spectra 5a and 5b with the corresponding 5c and 5d reveals the twofold benefits of using PENDANT rather than DEPT (135°). These are that isolated S nuclei can be detected simultaneously with $(I_n)S$ nuclei when using PENDANT, unlike DEPT which also reveals generally poorer S/N.

CONCLUSIONS

For pulse sequences that involve polarization transfer, or exchange, with the sensitive nucleus decoupled during detection of insensitive nuclei, it is demonstrated that the dominant relaxation of the sensitive nuclei can be accelerated by inverse polarization from the insensitive nuclei through the use of the magnetization of the latter that develops under NOE conditions during the acquisition of the FID. A simple pulse sequence (SNARE) that facilitates the implementation of the concept is proposed, and general conditions for its use in $\{^1H\} - {}^{13}C$ studies are suggested. In general the benefits of SNARE are greater the longer the acquisition time and the shorter the intersequence relaxation delay. It is shown that there is a range of spectral-acquisition parameters of practical interest for which the method can be beneficial. It is possible that SNARE should be capable of advantageously replacing the relaxation delay in many pulse sequences, including those that are designed to yield multidimensional spectra.

ACKNOWLEDGMENTS

REFERENCES

1. O. A. Gansow and A. R. Burke, *J. Chem. Soc., Chem. Commun.,* 456 (1972).
2. J. Homer and S. U. Patel, *J. Chem. Soc., Faraday Trans.* **86,** 215 (1990).
3. A. A. Maudsley and R. R. Ernst, *Chem. Phys. Lett.* **50,** 368 (1977).
4. G. A. Morris and R. Freeman, *J. Am. Chem. Soc.* **101,** 760 (1979).
5. M. R. Bendall, D. M. Dodrell, and D. T. Pegg, *J. Am. Chem. Soc.* **103,** 4603 (1981).
6. J. Homer and M. C. Perry, *J. Chem. Soc., Chem. Commun.,* 373 (1994).
7. H. Kessler, M. Gehrke, and C. Griesinger, *Angew. Chem.* **27,** 490 (1988); R. R. Ernst, G. Bodenhausen, and A. Wokaun, ''Principles of Nuclear Magnetic Resonance in One and Two Dimensions,'' Clarendon, Oxford, 1987.
8. G. Bodenhausen and D. J. Ruben, *Chem. Phys. Lett.* **69,** 85 (1980).
9. R. K. Harris and R. H. Newman, *J. Magn. Reson.* **24,** 499 (1976).