

Evaluation of possible nuclear magnetic resonance diagnostic techniques for tokamak experiments

S. J. Zweben,^{a)} T. W. Kornack, D. Majeski, G. Schilling, C. H. Skinner, and R. Wilson
Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543

N. Kuzma
Princeton University, Princeton, New Jersey 08540

(Received on 8 July 2002)

Potential applications of nuclear magnetic resonance (NMR) diagnostic techniques to tokamak experiments are evaluated. NMR frequencies for hydrogen isotopes and low- Z nuclei in such experiments are in the frequency range ≈ 20 – 200 MHz, so existing rf antennas could be used to rotate the spin polarization and to make the NMR measurements. Our tentative conclusion is that such measurements are possible if highly spin polarized H or ^3He gas sources (which exist) are used to fuel these plasmas. In addition, NMR measurements of the surface layers of the first wall (without plasma) may also be possible, e.g., to evaluate the inventory of tritium inside the vessel. © 2003 American Institute of Physics. [DOI: 10.1063/1.1530388]

I. INTRODUCTION

The use of nuclear magnetic resonance (NMR) for physical, chemical and biological studies is very well developed and highly successful.^{1–3} Modern NMR spectrometers measure the resonances between an applied oscillating rf magnetic field and the nuclear spin states of a sample in a strong dc magnetic field. The NMR frequency and spin relaxation times vary with the local electronic and molecular environment, so NMR is used for quantitative chemical analysis of solids, liquids, and gases. Modern NMR devices can measure the structure of μm -sized biological cells and even a single quantum dot on a 10 nm scale.

As far as we know there have been no attempts to use magnetic resonance to measure the properties of plasmas. However, there was a significant effort starting in 1982 to evaluate the properties of spin polarized nuclei in tokamak plasmas with the goal of increasing the fusion reaction rate.^{4–6} Those articles calculated many of the relevant interactions between nuclear spins and the fusion plasmas which are of interest for plasma diagnostic applications. There was also an attempt to explain ion cyclotron emission in terms of spin-flip transitions.⁷

The present article examines some possible applications of NMR techniques to tokamak experiments. In general, NMR measurements on magnetized plasmas are difficult due to their low density and to the complexity of rf wave propagation in plasmas. However, our tentative conclusion is that such measurements are possible if highly spin polarized hydrogen or ^3He gas sources (which exist) are used to fuel these plasmas. In addition, NMR measurements of the surface layers of the first wall (without plasma) are also possible, e.g., to evaluate the inventory of tritium inside the vessel.

^{a)}Electronic mail: szweben@pppl.gov

II. NMR IN PLASMAS

A. Background

As illustrated in Table I, many low- Z nuclei have non-zero nuclear spin and so can potentially be used for NMR measurements in tokamaks.^{1–3} For example, the NMR frequency of a proton in a magnetic field of $B=2.35$ T is $f_{\text{NMR}}=2\mu B/h\approx 100$ MHz, where μ is the nuclear magnetic moment of the proton. Normally only a very small fraction $F_{\text{spin}}\approx\mu B/kT$ of the nuclei contribute to the NMR interaction in thermal equilibrium, e.g., for a proton with $\mu\approx 1.4\times 10^{-26}$ J/T, $F_{\text{spin}}\approx 8\times 10^{-6}$ at this field at room temperature.

In a conventional pulsed NMR measurement, the sample is placed in a highly uniform magnetic field of typically $B\leq 10$ T and an rf driver coil outside the sample applies a pulse of oscillating magnetic field B_1 transverse to B . This B_1 pulse rotates the nuclear spins from their equilibrium direction along B to a transient state with their net spins aligned transverse to B . After the driving rf field is turned off, these spins then begin to precess about B at f_{NMR} and produce a transverse magnetic field $B_\perp=\mu_0 M_\perp$, where $M_\perp=n\mu$ is the transverse magnetization, n is the net density of nuclear spins, and $\mu_0=4\pi\times 10^{-7}$. The relaxation of these spins back to equilibrium, called the “free induction decay” (FID), can be measured with a rf antenna. The maximum output signal is the rf voltage induced in the pickup coil

$$V(\text{volts})=NA\omega_{\text{NMR}}B_\perp\propto(\mu^3B^2)(n/kT), \quad (1)$$

where N is the number of turns in the pickup coil of area $A(\text{m}^2)$, ω_{NMR} is the NMR frequency (rad/s), and B_\perp is the transverse magnetic field (T). For example, for 1 cm^3 of liquid water at room temperature with $B=1$ T, $F_{\text{spin}}\approx 4\times 10^{-6}$, $B_\perp\approx 3.4\times 10^{-10}$ T, and for coil with $N=10$ turns at $A=10^{-4}\text{ m}^2$ per turn, the NMR signal voltage is $V\approx 10^{-3}$ V.⁸ The relative signal level or “sensitivity” depends

TABLE I. Nuclear magnetic resonance parameters.

Particle	Spin	$f_{\text{NMR}}(\text{MHz})^a$	$f_{\text{NMR}}/f_{\text{ci}}^b$	Sensitivity ^c
Hydrogen	1/2	100	2.8	1.00
Deuterium	1	15.35	0.86	0.009
Tritium	1/2	106.7	9.0	1.2
³ He	1/2	76.2	3.2	0.44
⁶ Li	1	14.7	0.82	0.009
⁷ Li	3/2	38.9	2.5	0.29
⁹ Be	3/2	14.1	0.89	0.014
¹⁰ B	3	10.7	0.6	0.02
¹¹ B	3/2	32.1	2	0.17
¹³ C	1/2	25.1	1.5	0.016

^aAt $B=2.3488$ T, from Ref. 1.

^bFor fully ionized nuclei, equal to $f_{\text{NMR}}/f_{\text{ci}}=(1/2)(\mu/\mu_N)(M_i/M_p)(1/Z)$.

^cRelative to protons at constant B for equal number of nuclei.

linearly on the sample density, linearly on the coil area, on the square of B , and on the cube of the nuclear moment (see Table I).

B. Difficulties of NMR in plasmas

There are several properties of plasmas which make NMR measurements more difficult than those on solids or liquids, for example: (1) low density and high temperature, (2) highly nonuniform B field, (3) short ion confinement time and ion cyclotron orbital motion, and (4) complexity of rf wave propagation and rf “noise” near the NMR frequency. The following paragraphs discuss these difficulties for the case of ³He nuclei Alcator C-Mod, where the maximum rf frequency of 80 MHz corresponds to a NMR resonance at $B=2.5$ T, and where typically $n_i \approx n_e \approx 2 \times 10^{14} \text{ cm}^{-3}$, $T_i \approx T_e \approx 2$ keV.

If the nuclear spins of the plasma were in equilibrium at the room temperature, then the NMR signal for plasma protons at a given B would be smaller than that for water at room temperature by the density ratio [see Eq. (1)], e.g., for an ohmic Alcator C-Mod plasma roughly $\approx [2 \times 10^{14} \text{ cm}^{-3}]/(7 \times 10^{22} \text{ cm}^{-3}) \approx 3 \times 10^{-9}$. The signal would be another $\approx 10^5$ times smaller if the plasma spins were at the plasma temperature. However, it is now possible to produce nearly 100% polarized hydrogen⁹ or ³He gas¹⁰ which could be used to fuel the plasma. Assuming for the moment that the plasma retains this polarization (see below), the resulting signal for the plasma NMR becomes larger by $(1/F_{\text{spin}})$, where $F_{\text{spin}} \approx 8 \times 10^{-6}$ for protons at $B=2.35$ T at room temperature. Thus the NMR signal from a fully polarized proton plasma would be $\approx 3 \times 10^{-9}/8 \times 10^{-6} \approx 4 \times 10^{-4}$ times that from liquid water, i.e., a plasma of area $\approx 1 \text{ m}^2$ would have a NMR signal comparable to $\approx 1 \text{ cm}^3$ of water (which was measurable in the 1940s).

However, the highly nonuniform B field in a toroidal plasma presents a major difficulty, since the NMR frequency of all species will vary as $1/R$ with respect to the plasma major radius R . Although this does allow spatial localization during the B_1 “drive” similar to that used in magnetic resonance imaging (MRI), the relatively large ΔB over which these driven spins resonate will cause them to decohere rapidly during the FID. For example, if a B_1 pulse is applied with $\Delta f/f \approx 1\%$ (i.e., $\Delta f \approx 0.8$ MHz with $\tau_{\text{rf}} \approx 1 \mu\text{s}$), then the

NMR resonance would occur over a width $\sigma_{\Delta B} \approx (\Delta B/B)\omega_{\text{NMR}} \approx 1$ MHz, resulting in a $\approx 1 \mu\text{s}$ decay time for the FID. This broad spectrum decreases the signal/noise with respect to conventional NMR spectroscopy, which is done in a highly uniform B field (the applied gradient in MRI is turned off during the FID).

Furthermore, the high speed of plasma ions also causes broadening of the NMR resonance in plasmas. For example, if the NMR resonance region has a radial width of $\Delta B/B \approx 1\%$, e.g., $\Delta R \approx 0.7$ cm in Alcator C-Mod, the ions would move out of the resonance region due to their poloidal motion with a frequency $\sigma_{\text{pol}} \approx (v_i/\Delta R)(B_{\text{pol}}/B) \approx 1$ MHz in Alcator C-Mod. Other broadening effects due to the finite ion gyroradius, the ion Doppler shift, and ion radial diffusion should be small compared to σ_{pol} .

Finally, another major difficulty for plasma NMR is the complexity of rf wave propagation into and out of the plasma. In general, the relationship between the NMR frequency and the ion cyclotron frequency is

$$f_{\text{NMR}}/f_{\text{ci}} = (1/2)(\mu/\mu_N)(M_i/M_p)(1/Z), \quad (2)$$

where μ is the nuclear moment, μ_N is the nuclear magneton, and the ion has a charge Z and a mass M_i with respect to the proton mass M_p . For most cases $f_{\text{NMR}} > f_{\text{ci}}$ (Table I), so rf waves near f_{NMR} should propagate relatively well in tokamaks. However, there is also spontaneous rf emission from the plasma which will be a “background” for any NMR measurements. These issues are discussed in more detail in Secs. III B and III C.

C. Nuclear spin relaxation processes in plasma

In their analysis of the possibility of spin-polarized fusion plasmas, Kulsrud *et al.*^{4–6} calculated various relaxation rates for the polarization of deuterium and tritium nuclei in the core of a magnetic fusion plasma with $B=5$ T, $n = 10^{14} \text{ cm}^{-3}$ and $T=10$ keV. They concluded that the cross section for depolarization through binary collisions is small compared to the fusion reaction cross section, so collisional spin relaxation should be negligible for magnetic fusion plasmas of interest. They also showed that ionization, charge exchange, and recombination will not significantly change the spin state of hydrogen isotopes in this strong magnetic field; thus the net polarization of the plasma (in the absence of other depolarization mechanisms) should retain the polarization of the neutrals used to fuel the plasma. They also showed that ion thermal and ion cyclotron motion in a sheared inhomogeneous magnetic field should cause a negligible depolarization, even with collisions. However, when a polarized nucleus contacts the wall surface it can depolarize rapidly;¹¹ therefore the polarization will tend to decay on a particle confinement time. Thus, without direct fueling by polarized nuclei, the plasma spins would most likely retain the net polarization of their source, which could be the first wall (for recycling species), or the fueling source from gas puffing, pellets, or neutral beam injection.

The only other source of nuclear spin depolarization identified by Kulsrud *et al.* is that due to internal plasma magnetic fluctuations in the frequency range

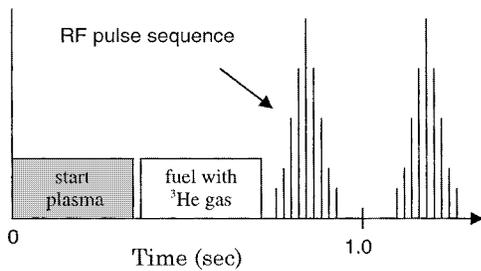


FIG. 1. Scenario for NMR measurements in a tokamak plasma.

$\approx (1/2 - 2)\omega_{\text{NMR}}$. A rough estimate for the amount of depolarization rate $\sigma_{\delta B}$ for tritons due to a left circularly polarized wave with a mean-square amplitude δB_{\perp} perpendicular to B was:⁵ $\sigma_{\delta B} \approx 1/8 (\delta B_{\perp}/B)^2 \omega_{\text{NMR}}$. Thus for $B = 5$ T and an assumed $\delta B_{\perp} \approx 10^{-4}$ T, tritons would depolarize within ≈ 75 ms, which is short compared with the triton particle confinement time. Thus, if there were no other faster decorrelation mechanisms, a measurement of the decorrelation rate of nuclear spins could potentially be used as a diagnostic for internal magnetic field fluctuations, assuming the gas fueling rate is faster than the internal decorrelation time.

III. NMR MEASUREMENTS ON A TOKAMAK

A tokamak is a toroidal magnetic chamber which contains a hot plasma used for fusion research. A typical tokamak plasma has a major radius $R = 1$ m, a minor radius $a = 0.3$ m, and toroidal magnetic field of $B = 3$ T. The plasma has a typical density of $n = 10^{14}$ cm⁻³ and is made from hydrogen or helium isotopes (H, D, T, ²He, or ³He), but also can contain trace amounts of the first wall material (e.g., C, Be, B, Fe). The toroidal magnetic field ($B \propto 1/R$) is pulsed for about 1 s every 1000 s. Since the plasma temperature is $T \approx 1$ keV, no material probes can be inserted into the tokamak plasma during operation.

A general scenario for NMR measurements in a tokamak is illustrated in Fig. 1. The plasma would be started as usual but would then be fueled with a highly spin-polarized gas. Just after fueling is completed, a series of rf B_1 pulses of various amplitudes would be applied through a rf antenna, and after each pulse the FID would be measured by the same (or another) rf antenna. This pulse sequence and FID measurement would be repeated later on until the NMR response has diminished to nearly zero.

A. Estimate of NMR signal

For clarity, we will initially assume that the tokamak is Alcator C-Mod and that the polarized fuel is ³He. The existing rf system has antennas tuned to a maximum frequency of 80 MHz, which corresponds to a ³He NMR resonance at $B \approx 2.5$ T. Assuming for the moment that *all* ³He ions in the plasma have their spins rotated 90° by the rf pulse to produce the maximum transverse magnetic field, the NMR signal can be estimated as follows (see Sec. II A): $M_{\perp} = n\mu \approx (2 \times 10^{20} \text{ m}^{-3})(2.1)(5 \times 10^{-27} \text{ J/T}) = 2.1 \times 10^{-6}$ A-turn/m, thus $B_{\perp} = \mu_0 M_{\perp} \approx (4\pi \times 10^{-7})(2.1 \times 10^{-6} \text{ A-turn/m}) = 2.6 \times 10^{-12}$ T and so $V_{\text{NMR}} = NA \omega_{\text{NMR}} B_{\perp} \approx (0.3 \text{ m}^2)(5 \times 10^8 \text{ rad/s})(2.6 \times 10^{-12} \text{ T}) \approx 4 \times 10^{-4}$ V.

However, in toroidal geometry only a small fraction of the plasma ions would be resonant with a given rf pulse due to the $(1/R)$ toroidal field (as usual for ion cyclotron resonance heating). Assuming a rf driver pulse of duration $\tau_{\text{rf}} \approx 1$ μ s (i.e., with a 1 MHz bandwidth at 80 MHz), only the ³He nuclei within $\Delta B/B \approx \Delta R/R \approx 1\%$ on a vertical cylinder at $R = R_0$ would be resonant. This $\Delta R \approx 0.7$ -cm-wide region would contain $\approx 2\%$ of the plasma ions. Since the NMR signal is proportional to the number of resonant ions, the NMR voltage at the antenna would be $V_{\text{NMR}} \approx (0.02)(4 \times 10^{-4}) \approx 10^{-5}$ V. The spectrum of the FID after the rf pulse would have a bandwidth of ≈ 1 MHz due to the finite ΔB and poloidal ion motion, as discussed in Sec. II B.

Therefore it seems possible to detect the NMR response of a fully polarized tokamak plasma. The detected signal could be calibrated by using a known pressure of polarized ³He gas in the chamber (without a plasma). The “tipping angle” of the rotated spins could be determined by finding the maximum response versus the rf pulse amplitude, and various pulse sequences could be tried. Fueling with polarized ³He gas should be feasible as long as a small magnetic field is applied to the gas bottle and the interactions with the tube surface are minimized by a reasonably fast flow rate.

B. Estimate of noise and background levels

The main background for conventional NMR measurements is the thermal noise in the rf detector, $V_{\text{th}} = (4kT_{\text{det}}\Omega\Delta f)^{1/2}$, where k is Boltzmann’s constant, T_{det} is the detector temperature (K), Ω is the detector resistance (ohms), and Δf is the signal bandwidth (Hz). Thus for a rf antenna at room temperature with a resistance of $\Omega = 50$ Ω , the thermal noise for a bandwidth of 1 MHz is $V_{\text{th}} \approx 10^{-6}$ V, which is about 0.1 times the expected NMR signal. This noise level is unusually large for NMR measurements due to the large bandwidth of the plasma NMR signal compared with that of liquids or solids.

Another source of noise would be the “ion cyclotron emission” (ICE) normally seen as rf emission from tokamaks at harmonics of ω_{ci} .^{7,12} This noise level would need to be measured on each machine, but for the Joint European Torus (JET) it was typically -80 dBm in the absence of fusion products (as would be the case for ³He in Alcator). For an antenna of $R = 50$ Ω this would produce a noise voltage of $V_{\text{ICE}} \approx 2 \times 10^{-5}$ V, which is about twice the expected NMR signal. Therefore ICE emission could be a significant noise source.

Another background in these plasma NMR measurements would be the low- Z nuclei on the first wall surface within the range of radii at the resonant B field. Although the number of ³He nuclei on the surface would be negligible, there would be a NMR resonance with H nuclei at a radius 0.76 times that at which the ³He resonate (see Table I). Assuming $\approx 10^4$ monolayers of H on the first wall, the surface density would be $\approx 10^{20}$ atoms/cm², of which only a small fraction $F_{\text{spin}} \approx 10^{-5}$ would be polarized at room temperature. Thus the number of nuclei per cm² of wall surface would be $\approx 10^{14}$ cm⁻², whereas the density of resonant ³He nuclei in the plasma would be $\approx (2 \times 10^{14} \text{ cm}^{-3})(50/\text{cm})$

$\approx 10^{16}$ atoms/cm², i.e., the plasma signal should be ≈ 100 times this background. Note that the D resonance would be outside the machine since its NMR frequency is so low (see Table I).

C. Propagation of rf and NMR signal

It is well known that rf waves can propagate from antennas to the plasma center at frequencies well above the ion cyclotron frequency ω_{ci} , so these waves should be able to penetrate to the plasma center to rotate the nuclear spin polarization. However, these fast Alfvén waves normally have only a small component of polarization in the direction perpendicular to B (which is needed to rotate the nuclear polarization of ³He), although this would probably be sufficient given the large rf power available in existing tokamak experiments (≈ 1 – 10 MW). Due to the complexity of this propagation the magnitude of these waves cannot be accurately predicted, therefore the rf pulse amplitude would have to be varied in order to calibrate the angle of spin tipping (see Fig. 1). Similarly, the small fluctuating magnetic fields caused by the nuclear precession during the FID inside the plasma center should be able to propagate to the rf antennas to be detected. This would most likely occur through the conversion to fast Alfvén waves near the center, although the efficiency of this process is not well known.

D. Magnetic field fluctuation measurement

Perhaps the most interesting NMR application to a tokamak would be a measurement of the internal magnetic field fluctuations. As noted in Sec. II C, transverse magnetic field fluctuations δB_{\perp} in the NMR frequency range are the most likely source of nuclear depolarization inside a hot plasma; thus if the decay time of the spin polarization can be measured, then this might be used to infer δB_{\perp} . However, since the nuclei in a tokamak circulate rapidly around a flux surface, this would measure the average δB_{\perp} over the ³He ion orbits, rather than its local value at the NMR resonance.

In principal, this spin decorrelation time could be measured as a function of minor radius (by varying the applied rf frequency or bandwidth), or as a function of the fluctuation frequency at a given radius using different species, e.g., D for low and T for high frequency waves. The frequency spectrum of this δB_{\perp} measurement might also be “fine tuned” by varying the parallel wave number of the rf driving waves, thus varying the effective NMR frequency.⁵ The response of the net polarization to a known δB_{\perp} could be calibrated by introducing known rf waves via the external antennas; in fact, the NMR measurement process itself should produce a few-% depolarization per rf pulse, equal to the fraction of resonant spins in the plasma.

However, it should be noted that a plasma magnetic fluctuation level of $\approx 10^{-4}$ T would be $\approx 10^8$ times larger than the fluctuating magnetic field expected from the nuclear spin precession (see Sec. III A). Thus the fluctuating plasma magnetic fields could potentially be a large source of background in these experiments. It is somewhat surprising that these plasma fluctuations are not already detected at the rf anten-

nas as ICE; perhaps this is due to their relatively short coherence length compared to the rf wavelength.

E. Species measurement

One of the main uses of NMR in solids and liquids is to identify the chemical composition of samples *via* the spectrum of the NMR response. It would be useful if NMR could be used to measure the H/D/T species mix and low-Z impurity content of the plasma. However, the large variation of magnetic field across the plasma causes the NMR resonances of several species to overlap, e.g., at a given NMR frequency the H resonance would be at a radius 1.06 larger than the T resonance. Also, each of these species would probably need to be highly polarized to be measurable. Thus it does not seem feasible to use NMR to determine the species mix inside the plasma in a tokamak (however, this technique might be usable in a linear plasma device with a uniform B).

F. Surface measurements (without plasma)

NMR techniques could potentially be used to measure the surface composition of the first wall in the absence of plasma. These surface layers are typically composed of ≈ 10 – 100 - μm -thick coatings of low-Z elements, several of which have NMR responses (see Table I), e.g., tritium, Li, Be, and B. This measurement could use the near fields from the normal rf antennas, or specially designed rf drive/pickup coils positioned using a remotely controlled arm inside the vessel. These fields should fully penetrate these coatings since the rf skin depths at 100 MHz are ≈ 50 μm in stainless steel and 2 mm in carbon. The NMR signal levels would be ≈ 100 times lower than for a fully polarized plasma (see Sec. III B); however, the noise from ICE would be absent, and the NMR pulse could be repeated many times during a toroidal field pulse to increase the signal-to-noise level.

A special application of this measurement could be used to evaluate the tritium inventory inside a fusion device like JET or the International Thermonuclear Experimental Reactor. Tritium has the largest magnetic moment of any nucleus, and tritium levels as low as 0.1 mCi have been measured using NMR.¹³ This technique could potentially scan over R by varying B , and could be calibrated using known tritium gas concentrations in the vessel. It might also be possible to use the nearly constant vertical field instead of the toroidal field for such measurements. Wall samples could also be removed from the chamber for analysis in a conventional NMR spectrometer.

ACKNOWLEDGMENTS

The authors thank W. Arunasalam, W. Happer, D. W. Johnson, and R. Kulsrud for their helpful comments. This work was performed under DOE Contract No. DE-AC02-76CHO3073.

¹R. J. Abraham, J. Fisher, and P. Loftus, *Introduction to NMR Spectroscopy* (Wiley, Chichester, UK, 1988).

²F. A. Bovey *et al.*, *Nuclear Magnetic Resonance Spectroscopy*, 2nd ed. (Academic, San Diego, 1988).

³P. J. Hore, *Nuclear Magnetic Resonance* (Oxford University Press, Oxford, UK, 1995).

- ⁴R. M. Kulsrud, H. P. Furth, E. J. Valeo, and M. Goldhaber, *Phys. Rev. Lett.* **49**, 1248 (1982).
- ⁵R. M. Kulsrud, E. J. Valeo, and S. C. Cowley, *Nucl. Fusion* **26**, 1443 (1986).
- ⁶S. C. Cowley, R. M. Kulsrud, and E. Valeo, *Phys. Fluids* **29**, 430 (1986).
- ⁷W. Arunasalam, G. J. Greene, and K. M. Young, *Nucl. Fusion* **34**, 927 (1994).
- ⁸F. Bloch, *Phys. Rev.* **70**, 460 (1946).
- ⁹R. W. Cline, T. J. Greytak, and D. Kleppner, *Phys. Rev. Lett.* **47**, 1195 (1981).
- ¹⁰T. E. Chupp, M. E. Wagshul, K. P. Coulter, A. B. McDonald, and W. Happer, *Phys. Rev. C* **36**, 2244 (1987).
- ¹¹H. S. Greenside, R. V. Budny, and D. E. Post, *J. Vac. Sci. Technol. A* **2**, 619 (1984).
- ¹²G. A. Cottrell and R. O. Dendy, *Phys. Rev. Lett.* **60**, 33 (1988).
- ¹³E. A. Evans *et al.*, *Handbook of Tritium NMR Spectroscopy* (Wiley-Interscience, Chichester, UK, 1985).