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Journal of Magnetic Resonance 171 (2004) 253–257
JMR Journal of Magnetic Resonance
www.elsevier.com/locate/jmr

Magnetic relaxation dispersion probe

Ken Victor, Vytas Kavolius, Robert G. Bryant*

Chemistry Department, University of Virginia, Charlottesville, VA 22904-4319, USA

Received 25 June 2004; revised 27 August 2004
Available online 25 September 2004

Abstract

The magnetic field dependence of nuclear spin–lattice relaxation rates provides a powerful approach to characterizing intra and intermolecular dynamics. NMR spectrometers that provide extensive magnetic relaxation dispersion profiles may switch magnetic field strengths rapidly by either moving the sample or by changing the current in an electromagnet. If the sample is moved, the polarization and detection fields may be very high, which provides both high sensitivity and resolution. This report summarizes the design of a pneumatic sample transport system for glass sample containers that may be used in either a dual magnet spectrometer or in a single magnet system that exploits the fringe field as the secondary magnetic field.

Keywords: Magnetic relaxation dispersion; MRD probe; Pneumatic probe design; Sample transit

1. Introduction

The magnetic field dependence of spin–lattice relaxation rates provides important information about the nuclear spin relaxation mechanisms and dynamics of the molecules studied. Multifield studies generally suffer from poor or variable sensitivity because the detection sensitivity in a NMR experiment varies nearly as the square of the magnetic field strength [1]. The classic solution to this problem is to make the magnetic field time dependent either by moving the sample or by switching the current in an electromagnet [2–9]. The magnetic field homogeneity in a current switched instrument is generally insufficient to resolve different chemical shifts. However, if the sample is moved either from one magnet to another or from a homogeneous region to the fringe fields of a magnet, the polarization and detection may be done in a high resolution field that provides multinuclear capabilities as well as simultaneous analysis of multicomponent spectra or samples [7,10]. We have described a dual magnet system that utilized small plastic sample containers that were pneumatically moved rapidly from one field to another [7]; however, we have found that the Delrin sample containers suffered from three difficulties: (1) The Delrin contained small amounts of water that leached into the sample over the period of days. (2) The Delrin is porous to molecular oxygen and, over the experimental acquisition time, the oxygen concentration increases significantly for de-oxygenated samples. Samples are typically de-oxygenated to eliminate the high-frequency dispersion generated by the paramagnetic molecular oxygen that may complicate analysis of the observed MRD profile. (3) The Delrin may interact with sample components such as proteins and various anionic organic acids of low molecular weight that are frequently used as buffers and/or observed spins in MRD experiments. We describe here a modified design for the dual magnet system probe to accommodate glass sample containers. Most aspects of the approach may also be utilized in a variable stop position system that exploits the fringe field of a single magnet system [10].

* Corresponding author. Fax: +1 804 924 3567.
E-mail address: rgb4g@virginia.edu (R.G. Bryant).

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doi:10.1016/j.jmr.2004.08.025

2. The shuttle

The sample container is incorporated into a shuttle built of Delrin or polycarbonate as shown in Fig. 1. The glass component is a short 6 mm o.d. thick wall Wilmad tube held in the shuttle body with a thin film of Devcon 5-min epoxy and stabilized in the plastic receiver with $\frac{1}{4}$–20 threads. The threads run the length of the shuttle and also serve to receive two screws that seal the liquid sample in the shuttle as described below. The adhesion strength of the epoxy to the glass is excellent, but is far weaker to the plastic. However, the $\frac{1}{4}$–20 threads inside the shuttle body increase the surface area for epoxy adhesion to the Delrin and provide mechanical support to hold the glass as if the glass were threaded. Because we constructed the whole probe, the 6 mm glass tube was convenient; in systems incorporating commercial NMR probes, 5 mm sample tubes are obviously required.

The shuttle body is of sufficient length that its angular excursion inside the shuttle transport tube is small enough that the glass tube does not encounter the wall of the RF coil assembly during the transport cycle. A 5/8 in. ID Garolite tube is used for the transport guide because it is robust and has constant diameter. Though its surface is not as smooth as glass on the inside, the friction between the walls and the shuttle has not significantly affected performance.

The key feature of the shuttle design is the gas-tight liquid seal that is formed by two threaded inserts as shown in Fig. 1. The degassed liquid sample is first loaded into the glass portion of the shuttle and then the first screw/plug is inserted. This first insert may or may not include a protrusion into the glass sample tube that displaces sample from the glass tube. For the current design, the protrusion is routinely used and effectively serves two purposes: (1) It minimizes the total amount of sample required. (2) The protrusion ensures that the entire sample is located within the shimmed, homogenous field of the superconducting magnet. This feature minimizes potential sample mixing from regions of different homogeneity induced by the shuttle transport.

The first sample containment screw does not necessarily form a liquid-tight seal and is designed such that its threaded base does not rest against the top of the glass tube so that compression against the glass is avoided. The sample is sealed by introducing a spherical 3/16 in. neoprene ball above the first screw that is compressed by the end of the second screw. The length of the second screw (nylon) is adjusted so that the screw head lies below the impact barrier that forms the edge of the

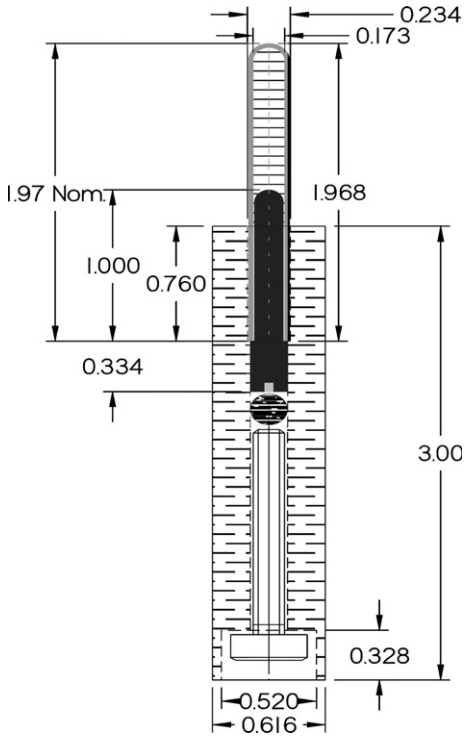

Fig. 1. The shuttle assembly. Dimensions shown are in inches. The main body of the shuttle is Delrin the glass sample insert is Wilmad 6 mm o.d. thick wall glass tube. The first spacer screw is also Delrin but may be other materials such as PEEK. The compression screw is nylon.

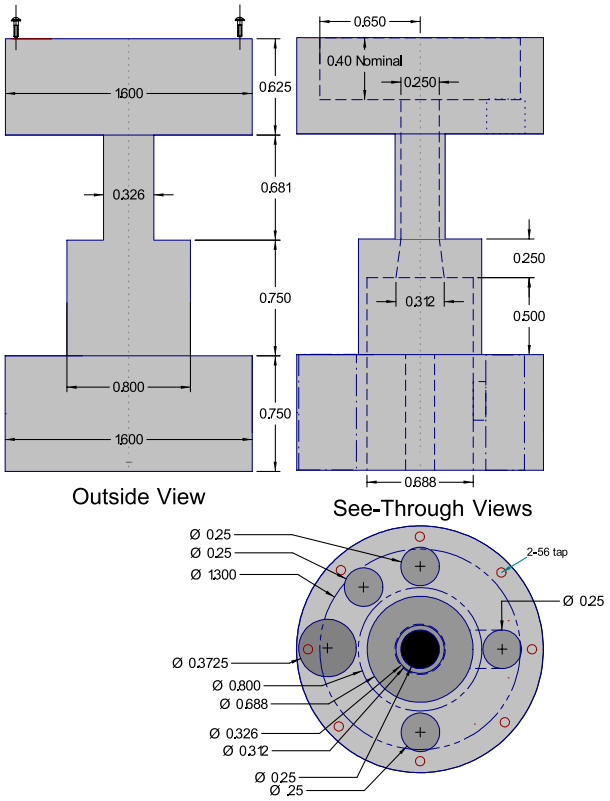

Fig. 2. The high-field stop portion of the probe head shown in three view. The RF coil is mounted on the thin wall of the narrowest portion of the assembly and then potted in epoxy to provide improved mechanical stability and reliability.

sample shuttle. The compression seal may be made with a cylindrical piece of 3/16 in. neoprene as well as a spherical one; however, the spherical design is reliable and convenient.

The glass sample tube essentially eliminates oxygen diffusion into the sample and minimizes surface effects induced by the sample components that compromised the utility of the completely plastic sample containers. In earlier designs we found that if the glass actually strikes the receiver section, the glass is pulverized. Therefore, because alignment of the glass in the shuttle is critical, the assembly with epoxy is done using a pair of precision self-aligning, coaxial alignment gigs. Failures of the glass tube occasionally occur at the junction between the glass and the Delrin barrel and are believed to be a consequence of stress fractures induced by the cumulative effects of energy dissipation from impacts at the stop positions at the ends of the shuttle probe in the two magnets. However, failures are rare and we typically get over 10^5 round trips without incident.

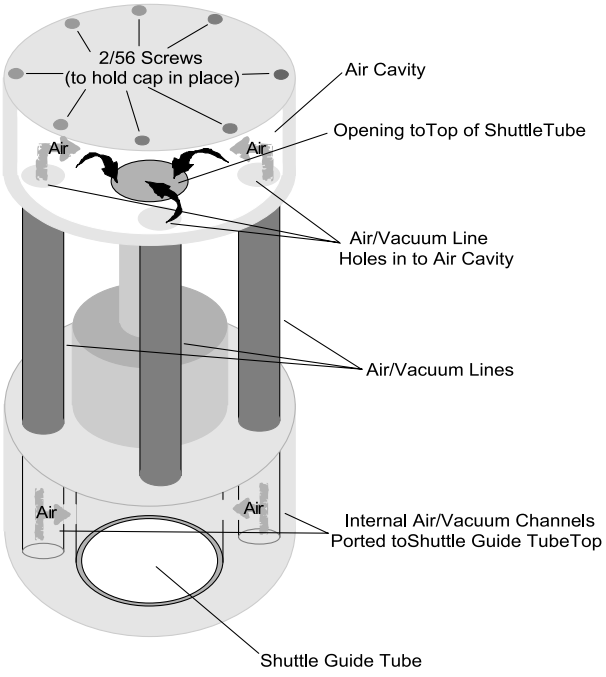

Fig. 3. The high-field stop portion of the probe assembly showing the air flow patterns provided by three supply lines.

Two major determinants of the shuttle transit time are the volume of air that can be delivered per unit time to the shuttle transit tube behind the sample shuttle and the displacement of the air in front of the sample shuttle. The delivered air volume is limited by the cross-sectional area of the air-delivery system, including orifices within the probe. To maximize the volume delivered per unit time and pressure, two paths for air delivery to the tube are employed as shown in Figs. 2 and 3. To initiate transit when the sample shuttle is to be moved from the superconducting magnet (top) to the electromagnet (below), a double solenoid directional air valve switches air pressure to the top reservoir of the probe to deliver air to the 0.25 in. diameter primary central port. At the same time, the solenoid may apply a vacuum to the stop position at the opposite end of the probe. Once the shuttle drops below the secondary ports located below the RF coil, additional air is delivered behind the moving shuttle through three additional ports, each of which is 0.25 in. in diameter. A similar arrangement is used at the remote stop position in the low field magnet.

The air-delivery system summarized schematically in Fig. 4 may operate in two modes: air only, and air/vacuum or push/pull. A vacuum reduces the pressure required to move the sample and increases speed as well

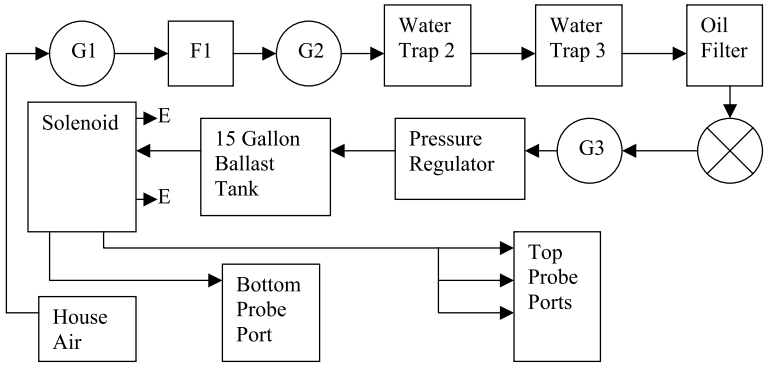

Fig. 4. Schematic summary of air supply system. House supply air is supplied through gauge G1 to a primary air and water filter, F1 (NAPA Gold Fuel Filter # 4389), followed by a second pressure gauge G2. Two bronze element water traps precede a high efficiency Bridgeport-Piedmont Company oil removal filter No. 707/208 that precedes a shut-off valve. From the valve the clean dry air passes through a Bridgeport-Piedmont Company No. 776/344 pressure regulator to a 15 gallon steel ballast tank. To this point all connections are made with 1/2 in. iron or brass pipe fittings. The dual solenoid is fed from the ballast tank by 1/2 in. high pressure hose. The solenoid, SMCModel NVS 4214-0552D is a 24 V dc device that connects to the top air reservoir of the probe via 3 1/4 in o.d. (0.17 in i.d). Polyethylene tubing (DAYCO Imperial Polyflow 44-PE-1/4 NSF-51); the solenoid connects to the bottom probe via a 1/4 in high pressure hose. The exhaust ports, E, may be connected to house vacuum, which is also isolated from the main by a 15 gallon ballast tank.

as impact at the stop positions. Both the house air and vacuum are connected to supply mains through ballast tanks that function to minimize pressure fluctuations and serve as final water and particulate traps after the primary filters in the supply line. The double throw dc solenoid valves are controlled by the TecMag pulse program as previously described [7]. The lines from the solenoid ports to the probe are split to increase the cross-section as shown in Figs. 2 and 3.

Critical damping of the shuttle once it reaches one of the stop positions may be a factor limiting reliable data acquisition with short delay times. Reliable damping is achieved using a passive cascade of washers positioned at the stop positions of the probe. The washers consist of a bonded sandwich of dB Block (Netwell, Minneapolis, MN) that was suggested by Professor A.G. Redfield and Neoprene. Bonding the 0.15 in. disk of 40 durometer closed cell neoprene to the dB Block washer minimizes impact degradation of the dB Block. The Neoprene section improves the damping bumper reliability but slows the damping time by approximately 50 ms. The central hole in the stop washer sandwich must be larger than the 6 mm o.d. glass sample which passes through it because the hole dimensions change on compression. If the clearance is insufficient, the glass tube may fail because of stresses imposed when the washer expands against the glass. A clearance of 0.070 in. is sufficient with the present materials.

The transit time for the sample as measured by the stability of the detected NMR signal is approximately 135 ms as shown in Fig. 5. This time includes the ~20 ms switching time for the double throw dc solenoid valve, the transit time for the sample to move 86 cm between the two magnets, and the settling time of the sample assembly at the stop position in the resonance field.

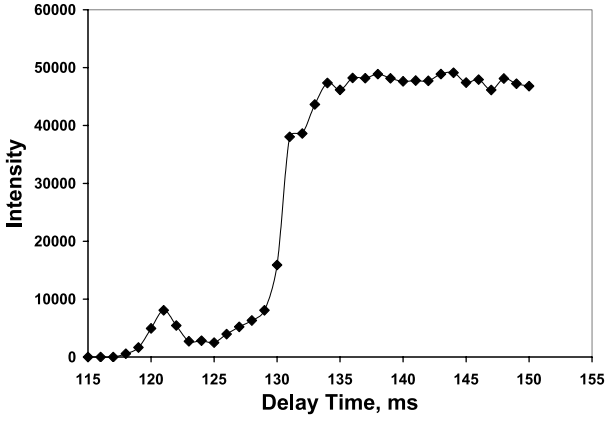

Fig. 5. The integrated proton NMR signal intensity of a water sample as a function of the delay time from the initiation of the pneumatic transfer from the satellite magnet. The transit distance is 86 cm and time is measured from the falling edge of the pulse that activates the dual solenoid valve for the sample transfer. The sample bounce is apparent as the first short time peak.

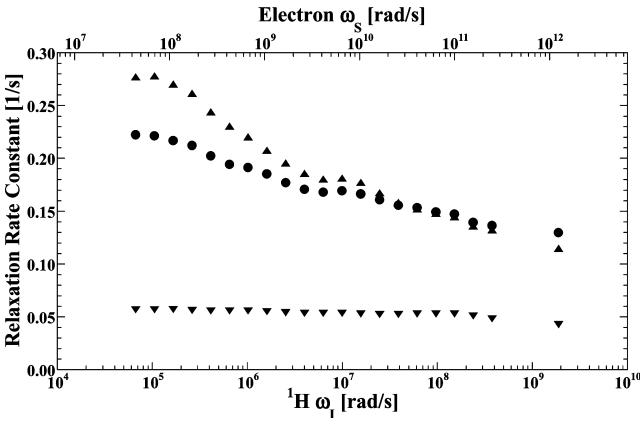

Fig. 6. The proton spin–lattice relaxation rate constants as a function of the magnetic field strength plotted as the proton Larmor frequency for the residual water (▼) proton resonance and the methyl (●) and methylene (▲) proton resonances of the ethanol obtained simultaneously for a sample of extruded 1000 Å diameter 1-palmitoyl-2-oleolyl-*SN*-glycero-3-phosphocholine (POPC, Avanti Polar Lipids) lipid vesicles solvated in D_2O with 1 M ethanol and with 50 mM total concentration of phospholipid.

Fig. 6 illustrates the simultaneous measurement of the MRD profiles for different spectral components of a POPC lipid vesicle sample containing 1 M ethanol in D_2O. The resonances for the residual water, methylene, and methyl protons were measured simultaneously and reveal different characteristics. The magnetic field dependence of the spin–lattice relaxation rate constant for the ethanol protons is coupled to the field dependence of the lipid protons more strongly than the residual protons. A more detailed interpretation will be presented elsewhere; however, we note that the frequency axis presentation is logarithmic and there is a wide range of dynamical information available from such measurements.

Acknowledgments

This work was supported by the National Institutes of Health, NIBIB 2805 and the University of Virginia. We acknowledge with gratitude a number of discussions with Professor A.G. Redfield concerning both theory and practice.

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