Communication

Design, construction, and validation of a 1-mm triple-resonance high-temperature-superconducting probe for NMR

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Abstract

We report a 600-MHz 1-mm triple-resonance high-temperature-superconducting (HTS) probe for nuclear magnetic resonance spectroscopy. The probe has a real sample volume of about 7.5 µl, an active volume of 6.3 µl, and appears to have the highest mass sensitivity at any field strength. The probe is constructed with four sets of HTS coils that are tuned to 1H, 2H, 13C, and 15N, and there is a z-axis gradient. The coils are cooled with a conventional Bruker CryoPlatform to about 20 K, and the sample chamber can be regulated above or below room temperature over a moderate range using a Bruker variable temperature unit. The absolute S/N for 0.1% ethylbenzene is approximately 1/3 that of a conventional 5 mm probe with just 1/70 of the sample volume. We demonstrate the utility of this probe for small molecules and proteins with 2D spectra of just 1.7 µg of ibuprofen and 400 µM 15N-labeled ubiquitin.

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1. Introduction

Nuclear magnetic resonance (NMR) is notoriously insensitive due to the very small equilibrium polarization at temperatures appropriate for biological samples and field strengths achievable with superconductive magnets. Signal-to-noise (S/N) can be improved with higher magnetic field strengths, by lowering the temperature of the sample, or by improving the performance of the radio frequency (RF) probe and electronics. RF probes can be improved in three general ways: First, reducing the volume of the detection coil increases the signal per nuclear spin [1], a concept that has been very effectively applied in copper solenoidal microcoils [2,3]. Second, cooling the coils and preamplifiers reduces noise by up to a factor of four [4]. Finally, coils built from low-loss materials such as superconductors improve the sensitivity [5–7].

We combined small sample volume with cryogenic cooling and high-temperature superconducting (HTS) technology [5–7] to build a 600 MHz 1-mm triple-resonance probe with a z-axis gradient (Fig. 1). This probe has an active volume of 6.3 µl and real sample volume of 7.5 µl. The sample is loaded vertically. Four nested Helmholtz pairs of resonant HTS coils (Fig. 1A) produce frequencies for 1H, 2H, 13C, and 15N. All eight HTS coils are cooled to about 20 K, and the 1H, 2H, and 13C preamplifiers are cooled to 77 K using a Bruker CryoPlatform. The 1-mm sample chamber is vacuum-insulated from the HTS coils and is warmed by a stream of air for temperature regulation. The 1H coil pair (Fig. 1B) has two features that allow it...
to be placed very close to the sample: First, the resonators, based on two distributed interdigital capacitors, with a spatial periodicity of only 0.125 mm, place a very low fringing electric field on the sample. Second, the current-carrying fingers are extensively slit to reduce shielding currents that would reduce $B_0$ homogeneity [7]. The $^1$H coil pair (Fig. 1D) also has a large height-to-width ratio to produce a homogeneous RF field. The $^2$H and $^{13}$C coils are spiral resonators. Lock sensitivity with such a small sample volume was given higher priority than carbon-observe sensitivity, and for this reason the $^2$H coils are in the second position from the inside, and the $^{13}$C coils are in the third position. On the outside are the $^{15}$N coils (Fig. 1C), also spiral resonators, to achieve a resonance frequency of 60 MHz. Because the $^{15}$N coils are far from the sample, their rather large electric field is acceptable. However, the simple spiral design supports additional modes at approximate multiples of 60 MHz. Final frequency-trimming relied upon extensive simulations to prevent these modes from interfering with the other coils.

Experimental performance of the probe is listed in Table 1. There is good agreement between the simulated ($^1$H B$_1$ homogeneity) and experimental value of 86.8% (Table 1). Electromagnetic simulations were carried out using IE3D (Zeland Software, Fremont, CA).

<table>
<thead>
<tr>
<th></th>
<th>$^1$H</th>
<th>$^{13}$C</th>
<th>$^{15}$N</th>
<th>$^2$H</th>
</tr>
</thead>
<tbody>
<tr>
<td>90° Pulse length @ power</td>
<td>9.5 µs @ 1.0 W</td>
<td>15 µs @ 18.5 W</td>
<td>48 µs @ 9.5 W</td>
<td>260 µs @ 80 mW</td>
</tr>
<tr>
<td>$B_1$ homogeneity</td>
<td>90.8% (450/90)</td>
<td>83.8% (360/0)</td>
<td>90.8% (360/0)</td>
<td>ND</td>
</tr>
<tr>
<td>$S/N$</td>
<td>86.8% (810/90)</td>
<td>80.6% (720/0)</td>
<td>65.4% (720/0)</td>
<td>ND</td>
</tr>
<tr>
<td>Lineshape$^a$</td>
<td>292 ± 28°</td>
<td>39°</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Spinning: 1.05/9.6/15.2 Hz</td>
<td></td>
<td>ND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-spinning: 0.88/13.9/20.9 Hz</td>
<td></td>
<td>ND</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Four measurements each on two different factory sealed 0.1% ethylbenzene, CDC$_3$ standards.

$^b$ 40% dioxane/C$_6$D$_6$ (ASTM standard).

$^c$ 2% chloroform, acetone-D$_6$ standard.
parameters such as predicted versus experimental resonance frequencies.

The S/N value of 292 ± 28 for 0.1% ethylbenzene (Table 1) is approximately 3.5-fold less than a standard 600 MHz 5-mm triple-resonance probe (S/N ~ 1000) with about 70-fold less sample. Thus, the mass sensitivity of the 1-mm HTS probe is about 20 times greater than a conventional 5-mm probe. Commercial 5-mm Bruker 600 and 800 MHz cryoprobes have S/N values, approximately 4000 and 8000, respectively. The 1-mm HTS probe has a mass sensitivity that is over four times greater than a 5-mm cryogenic probe at the same field strength and over two times greater than state-of-the-art 5-mm technology at 800 MHz.
Microsolenoid probes have extremely high mass sensitivity because of optimal filling factors [2,3,8,9]. To compare the 1-mm HTS, we measured the anomic $^1$H from two different 10.0 mM preparations of sucrose in D$_2$O using 1, 4, and 8 fully relaxed scans. Each condition was repeated three times for a total of 18 measurements. These yielded a S/N per μmole per scan of 2338 ± 134 for the active volume (6.3 μl) and 1964 ± 112 for the total volume of sample used (7.5 μl). Comparable measurements in a commercial 1-mm solenoid probe were 2130 for the active volume (1.5 μl) and 639 for the total volume of sample (5 μl) [8]. Thus, the 1-mm HTS probe has slightly better or similar absolute mass sensitivity and much better total volume sensitivity than a microsolenoid probe at the same field strength.

The extremely high mass sensitivity of this probe suggests that it may be useful for metabolomics [10], natural products [11], and protein screening applications [12,13]. Fig. 2 shows experimental results for ibuprofen at natural $^{13}$C isotopic abundance and $^{15}$N-labeled ubiquitin. The ibuprofen spectra (Figs. 2A–D and F) were collected with either 22.6 μg in 10 μl DMSO-D6 (11 mM) or 1.7 μg in 7.5 μl DMSO-D6 (1.1 mM). The ubiquitin $^{15}$N-HSQC spectrum (Fig. 2E) was collected with 400 μM ubiquitin in 8 μl phosphate buffer (pH 5.5) with 10% D$_2$O for lock.

The 11 mM ibuprofen spectra had extremely good S/N, including the natural abundance $^{13}$C-HMBC. We were also able to easily collect standard $^1$H 1D, high-resolution COSY, and $^{13}$C-HMQC data on 1.1 mM ibuprofen. High-quality $^{15}$N-HSQC spectra from 1 mM (data not shown) and 400 μM ubiquitin were collected in 10 and 41 min, respectively (Fig. 2E).

These results demonstrate that the 1-mm HTS triple-resonance probe is capable of very high-sensitivity measurements of small molecules and proteins. Although the absolute sensitivity makes it an impractical choice for full protein structural analysis, it can provide an economical screening platform for protein expression [12] and SAR-by-NMR [13] by requiring as little as 3 nmol of total protein at a concentration of less than 500 μM for each experiment.

Acknowledgments

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References