Formation of sensitive layer in experiments on NMR subsurface imaging of solids

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(Submitted 17 February 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 7, 348–350 (10 April 1988)

A new method of NMR subsurface imaging of solids is proposed. The method is based on the formation of a sensitive layer in the high-gradient magnetic field near the end of a superconducting solenoid. An experiment with a one-dimensional phantom has been carried out in order to estimate the spatial resolution. A resolution of better than 200 μm has been achieved.

1. The problem of obtaining satisfactory images of solids has not yet been solved in subsurface imaging by means of nuclear magnetic resonance. A fundamental difficulty stems from a circumstance which is common to all subsurface imaging methods which are based on the use of magnetic-field gradients **G**. This difficulty is the dependence of the spatial resolution (δz) which can be achieved along the z direction on the width of the NMR line, $\Delta\nu$, and the value of G_z (Ref. 1):

$$\delta z \approx \Delta\nu/\gamma G_z , \tag{1}$$

where γ is the gyromagnetic ratio of the resonating nuclei. Since values $\Delta\nu \sim 50$ kHz are typical of solids, it is not possible to obtain an acceptable resolution at the maximum values of G_z, $\leqslant 0.1$ T/m, which can be provided by conventional gradient systems.[2]

2. Several approaches which have been proposed for overcoming this difficulty[3–6] would use an artificial narrowing of the spectral lines of the objects of study. On the one hand, this measure would restrict the method to a fairly short list of samples for which a significant line contraction could be achieved; on the other hand, it presupposes the use of intense and uniform rf fields. Generating such fields in the case of real macroscopic objects is not a trivial problem.

3. In this letter we are proposing a new solution to the problem of increasing the spatial resolution δz within the framework of a method of selective subsurface imaging,[2] through the formation of a thin sensitive layer in the solid object. It follows from (1) that δz can be reduced by increasing the magnetic-field gradient G_z. A convenient source of high-gradient fields of this sort might be an axisymmetric magnet system, e.g., a solenoid with a large length-to-radius ratio L/R. In the first place, the gradient of the z component of the magnetic-induction vector near the axis of such a solenoid reaches a maximum near the end of the winding. This maximum value is

$$G_z^{max} \approx B_0/2R, \tag{2}$$

where B_0 is the field at the center of the solenoid. Second, the polarizing magnetic field in this region has the value $B = B_0/2$, which—given a sufficiently strong field B_0—would provide both the gradients G_z required and a high sensitivity for the NMR experiment.

4. The superconducting magnets which are used in NMR spectroscopy and the solenoids discussed above have similar field configurations. Accordingly, we made use of the end region of the magnet of a Bruker CXP-200 pulse NMR spectrometer ($B_0 = 4.7\ T$) with a thermal-aperture diameter of 79 mm. An estimate of the maximum field gradient in this region leads to the value $\gamma G_z \approx 1$ MHz/mm, leading us to expect $\delta z \lesssim 100\ \mu$m. The corresponding resonant frequency of ^{1}H nuclei would be about 100 MHz.

5. The ^{1}H NMR signals were excited at a frequency of 90 MHz by a solid-echo $90^\circ_x - \tau - 90^\circ_y$ pulse train. The lengths of the 90° pulses were chosen to be 10 μs, satisfying the conditions for selective excitation.[2] A sensitive layer with δz on the order of 0.1 mm was formed. The one-dimensional phantom consisted of four disks with a diameter $d = 5$ mm and a thickness of 1.5 mm, made of a material equivalent of Plexiglas. The disks were separated by glass spacers I, II, III with respective thickness of 1 mm, 0.6 mm, and 0.2 mm.

6. The spin density was scanned by the sensitive layer through a vertical displacement of the phantom. Figure 1 shows the intensity of the spin-echo signal as a function

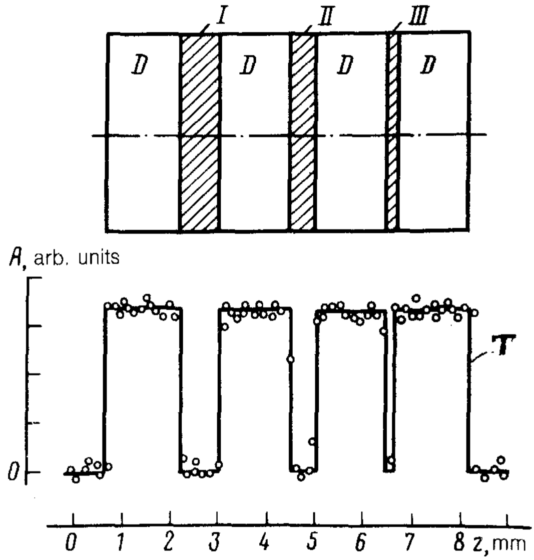

FIG. 1. *D*—Disk made of a material equivalent to Plexiglas; I, II, III—glass spacers; *T*—theoretical profile of the phantom.

of the displacement of the phantom along the magnet axis (z). This behavior faithfully reflects the geometry of the sample and proves that a spatial resolution of at least 200 μm is possible. The satisfaction of the condition $d \ll 2R$ ensures that the sensitive layer will be essentially planar within the sample.

7. This new method opens up opportunities for producing high-quality subsurface images of solid objects. A contrast in terms of relaxation times can be achieved by varying the delays between the pulses or by using multipulse trains of a spin-locking nature.[7]

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Translated by Dave Parsons